CHAPTER

# COSTING AND PROJECT EVALUATION

6

## CHAPTER CONTENTS



## KEY LEARNING OBJECTIVES

- How to estimate process capital and operating costs
- How to find and forecast prices for use in economic analysis
- How corporations finance projects
- Different criteria that companies use to compare the financial attractiveness of alternative projects, and other factors that are also taken into account in project selection
- How to allow for error in cost estimates

## 6.1 INTRODUCTION

Most chemical engineering design projects are carried out to provide information from which estimates of capital and operating costs can be made. Chemical plants are built to make a profit, and an estimate of the investment required and the cost of production are needed before the profitability of a project can be assessed. Cost estimation is a specialized subject and a profession in its own right, but the

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design engineer must be able to make rough cost estimates to decide between project alternatives and optimize the design.

This chapter introduces the components of capital and operating costs and the techniques used for estimating. Simple costing methods and some cost data are given, which can be used to make preliminary estimates of capital and operating costs in the early stages of design. Sources of cost data and methods for updating cost estimates are described. The main methods used for economic evaluation of projects are introduced, together with an overview of factors that influence project selection.

Most cost estimating and economic analysis calculations are easily carried out using spreadsheets. Templates are introduced in the examples throughout the chapter. Blank templates are given in Appendix G and in the online material at http://books.elsevier.com/companions. The more sophisticated software that is used in industry for preliminary estimating is discussed in Section 6.3.

For a more detailed treatment of the subject the reader should refer to the numerous specialized texts that have been published on cost estimation. The following books are particularly recommended: Happle and Jordan (1975), Guthrie (1974), Page (1996), Garrett (1989), Humphreys (1991) and Humphreys (2005).

Several companies regularly publish economic analyses of chemical processes. Nexant publishes the Process Evaluation and Research Planning (PERP) reports (www.nexant.com/products). Roughly ten new reports are issued each year and almost two hundred processes have been analyzed. The PERP reports provide estimates of capital and operating costs, usually for two or three process alternatives, as well as an overview of the market. Access Intelligence publishes the SRI Chemical Economics Handbook (CEH) series, which contains 288 reports on a range of commodity and specialty chemicals. The CEH reports provide an overview of production technologies and analyses of several regional markets, but do not provide the level of production cost detail given in the PERP reports. Various consulting firms also carry out paid economic studies of "state of the art" technology. Although there are minor variations in methodology, most of these studies estimate production costs using similar assumptions. The conventions used will be introduced in the following sections and should be followed when making preliminary economic analyses and when accurate cost information is not available.

## 6.2 COSTS, REVENUES AND PROFITS

This section introduces the components of project costs and revenues.

### 6.2.1 FIXED CAPITAL INVESTMENT

The fixed capital investment is the total cost of designing, constructing and installing a plant and the associated modifications needed to prepare the plant site. The fixed capital investment is made up of:

1. The inside battery limits (ISBL) investment – the cost of the plant itself.
2. The modifications and improvements that must be made to the site infrastructure, known as offsite or OSBL investment.
3. Engineering and construction costs.
4. Contingency charges.

### ISBL plant costs

The ISBL plant cost includes the cost of procuring and installing all the process equipment that makes up the new plant.

The direct field costs include:

1. All the major process equipment, such as vessels, reactors, columns, furnaces, heat exchangers, coolers, pumps, compressors, motors, fans, turbines, filters, centrifuges, driers, conveyors, etc., including field fabrication and testing if necessary.
2. Bulk items, such as piping, valves, wiring, instruments, structures, insulation, paint, lube oils, solvents, catalysts, etc.
3. Civil works such as roads, foundations, piling, buildings, sewers, ditches, bunds, etc.
4. Installation labour and supervision.

In addition to the direct field costs there will be indirect field costs including:

1. Construction costs such as construction equipment rental, temporary construction (rigging, trailers, etc.), temporary water and power, construction workshops, etc.
2. Field expenses and services such as field canteens, specialists' costs, overtime pay and adverse weather costs.
3. Construction insurance.
4. Labour benefits and burdens (social security, workers compensation, etc.).
5. Miscellaneous overhead items such as agent's fees, legal costs, import duties, special freight costs, local taxes, patent fees or royalties, corporate overheads, etc.

In the early stages of a project it is important to define the ISBL scope carefully, as other project costs are often estimated from ISBL cost. The overall project economics can be badly miscalculated if the ISBL scope is poorly defined. Methods for estimating ISBL costs are given in Section 6.3.

### Offsite costs

Offsite cost or OSBL investment includes the costs of the additions that must be made to the site infrastructure to accommodate adding a new plant or increasing the capacity of an existing plant. Offsite investments may include:

- Electric main substations, transformers, switchgear and power lines.
- Power generation plants, turbine engines, standby generators.
- Boilers, steam mains, condensate lines, boiler feed water treatment plant, supply pumps.
- Cooling towers, circulation pumps, cooling water mains, cooling water treatment.
- Water pipes, water demineralization, waste water treatment plant, site drainage and sewers.
- Air separation plants to provide site nitrogen for inert gas, nitrogen lines.
- Driers and blowers for instrument air, instrument air lines.
- Pipe bridges, feed and product pipelines.
- Tanker farms, loading facilities, conveyors, docks, warehouses, railroads, lift trucks.
- Laboratories, analytical equipment, offices, canteens, changing rooms, central control rooms.
- Workshops and maintenance facilities.
- Emergency services, fire fighting equipment, fire hydrants, medical facilities, etc.
- Site security, fencing, gatehouses, landscaping.

Offsite investments often involve interactions with utility companies such as electricity or water suppliers. They may be subject to equal or greater scrutiny than ISBL investments, because of their impact on the local community through water consumption and discharge, traffic, etc.

Offsite costs are typically estimated as a proportion of ISBL costs in the early stages of design. Offsite costs are usually in the range from 10% to 100% of ISBL costs, depending on the project scope and its impact on site infrastructure. For typical petrochemical projects, offsite costs are usually between 20% and 50% of ISBL cost, and 40% is usually used as an initial estimate if no details of the site are known. Offsite costs will generally be lower for an established site with well developed infrastructure. This is particularly true of sites that have undergone contraction, where some plants have closed, leaving underutilized infrastructure ("brownfield" sites). On the other hand, if the site infrastructure is in need of repair or upgrading to meet new regulations, or if the plant is built on a completely new site (a "greenfield" site) then offsite costs will be higher.

Once a site has been chosen for the project then the modifications to the site infrastructure that are needed can be designed in detail in the same manner as the ISBL investments. Infrastructure upgrades are usually the first part of a project to be implemented as they usually need to be commissioned before the plant can begin operation.

### *Engineering costs*

The engineering costs, sometimes referred to as home office costs or contractor charges, include the costs of detailed design and other engineering services required to carry out the project:

1. Detailed design engineering of process equipment, piping systems, control systems and offsites, plant layout, drafting, cost engineering, scale models and civil engineering.
2. Procurement of main plant items and bulks.
3. Construction supervision and services.
4. Administrative charges, including engineering supervision, project management, expediting, inspection, travel and living expenses and home office overheads.
5. Bonding.
6. Contractor's profit.

Very few operating companies retain a large enough engineering staff to carry out all of these activities internally, except for very small projects. In most cases, one or more of the major engineering contracting firms will be brought in.

Engineering costs are best estimated individually based on project scope, as they are not directly proportional to project size. A rule of thumb for engineering costs is 30% of ISBL plus OSBL cost for smaller projects and 10% of ISBL plus OSBL cost for larger projects. The actual charges paid for real industrial projects vary considerably from customer to customer and are strongly influenced by long-term client-contractor relationships and overall market demand for engineering services. Customers usually have to pay premiums or surcharges if they want to complete a project on an accelerated timeline or if they make a lot of changes once a project is underway.

### *Contingency charges*

Contingency charges are extra costs added into the project budget to allow for variation from the cost estimate. All cost estimates are uncertain (see Section 6.3.1) and the final installed cost of many items is not known until installation has been successfully completed. Apart from errors in the cost estimate, contingency costs also help cover:

- changes in project scope,
- changes in prices (e.g., prices of steel, copper, catalyst, etc.),
- currency fluctuations,
- labour disputes,
- subcontractor problems, and
- other unexpected problems.

A minimum contingency charge of 10% of ISBL plus OSBL cost should be used on all projects. If the technology is uncertain then higher contingency charges (up to 50%) are used. Contingency charges are discussed in more detail in Section 6.8.4.

## 6.2.2 WORKING CAPITAL

Working capital is the additional money needed, above what it cost to build the plant, to start the plant up and run it until it starts earning income. Working capital typically includes:

1. Value of raw material inventory – usually estimated as two weeks' delivered cost of raw materials.
2. Value of product and by-product inventory – estimated as two weeks' cost of production.
3. Cash on hand – estimated as one week's cost of production.
4. Accounts receivable – products shipped but not yet paid for – estimated as one month's cost of production.
5. Credit for accounts payable – feedstocks, solvents, catalysts, packaging, etc. received but not yet paid for – estimated as one month's delivered cost.
6. Spare parts inventory – estimated as 1% to 2% of ISBL plus OSBL investment cost.

It can be seen that the sum of items 1 through 5 is roughly seven weeks' cost of production minus two weeks' feedstock costs (item 5 is a credit).

Working capital can vary from as low as 5% of the fixed capital for a simple, single-product process, with little or no finished product storage, to as high as 30% for a process producing a diverse range of product grades for a sophisticated market, such as synthetic fibres. A typical figure for petrochemical plants is 15% of the fixed capital (ISBL plus OSBL cost).

Working capital is better estimated from the cost of production rather than capital investment. It is recovered at the end of the plant life.

Other methods for estimating the working capital requirement are given by Bechtel (1960), Lyda (1972) and Scott (1978).

## 6.2.3 VARIABLE COSTS OF PRODUCTION

Variable costs of production are costs that are proportional to the plant output or operation rate. These include the costs of:

1. Raw materials consumed by the process.
2. Utilities – fuel burned in process heaters, steam, cooling water, electricity, raw water, instrument air, nitrogen and other services brought in from elsewhere on the site.
3. Consumables – solvents, acids, bases, inert materials, corrosion inhibitors, additives, catalysts and adsorbents that require continuous or frequent replacement.

4. Effluent disposal.
5. Packaging and shipping – drums, bags, tankers, freight charges, etc.

Variable costs can usually be reduced by more efficient design or operation of the plant. Methods for estimating variable costs are discussed in Section 6.4.

### 6.2.4 FIXED COSTS OF PRODUCTION

Fixed production costs are costs that are incurred regardless of the plant operation rate or output. If the plant cuts back its production these costs are not reduced. Fixed costs include:

1. Operating labour – see Section 6.4.7.
2. Supervision – usually taken as 25% of operating labour.
3. Direct salary overhead – costs of fringe benefits, payroll taxes, health insurance, etc., usually 40% to 60% of operating labour plus supervision.
4. Maintenance, which includes both materials and labour, and is typically estimated as 3% to 5% of ISBL investment, depending on the expected plant reliability. Plants with more moving equipment or more solids handling usually require higher maintenance.
5. Property taxes and insurance – typically 1% to 2% of ISBL fixed capital.
6. Rent of land (and/or buildings) – typically estimated as 1% to 2% of ISBL plus OSBL investment. Most projects assume land is rented rather than purchased, but in some cases the land is bought and the cost is added to the fixed capital investment and recovered at the end of the plant life.
7. General plant overhead – charges to cover corporate overhead functions such as human resources, research and development (R&D), information technology, finance, legal, etc. Corporate overhead varies widely depending on the industry sector. Oil refining companies that carry out minimal R&D have much lower overhead than pharmaceuticals manufacturers. Plant overhead is typically taken as 65% of total labour (including supervision and direct overhead) plus maintenance.
8. Allocated environmental charges; for example, to cover Superfund payments in the United States, or costs associated with REACH in the European Union (see Section 9.1.1) – typically 1% of ISBL plus OSBL cost.
9. Running license fees and royalty payments – i.e., those not capitalized at the start of the project.
10. Capital charges – these include interest payments due on any debt or loans used to finance the project, but do not include expected returns on invested equity capital – see Section 6.6.
11. Sales and marketing costs – in some cases these are considered part of general plant overhead. They can vary from almost zero for some commodities to millions of dollars a year for branded items such as foods, toiletries, drugs and cosmetics.

Fixed costs should never be neglected, even in the earliest stages of design, as they can have a significant impact on project economics. Very few chemical plants in developed economies carry less than US$1 million (US$1 MM) of fixed costs.

Fixed costs are also a strong disincentive for building small plants. As plant size is increased, labour, supervision and overhead costs usually do not increase, and hence the fixed cost per kilogram of product decreases. This, together with economies of scale in capital investment (see Section 6.3) gives larger plants more flexibility to reduce prices and hence force smaller plants out of business during downturns in the business cycle.

Fixed costs are not easily influenced by better design or operation of the plant, other than improvements that allow the plant to be operated safely with a smaller workforce. Fixed costs are more amenable to control at the corporate level than the plant level.

## 6.2.5 REVENUES, MARGINS AND PROFITS

### *Revenues*

The revenues for a project are the incomes earned from sales of main products and by-products.

The production rate of main product is usually specified in the design basis and is determined based on predictions of overall market growth.

Determining which by-products to recover, purify and sell is usually more difficult than determining the main product. Some by-products are produced by the main reaction stoichiometry and are unavoidable unless new chemistry can be found. These stoichiometric by-products must usually be sold for whatever price they can get, otherwise waste disposal costs will be excessive. Some examples of stoichiometric by-products are given in Table 6.1. Other by-products are produced from feed impurities or by non-selective reactions. The decision to recover, purify and sell; recycle or otherwise attenuate; or dispose of them as wastes is an important design optimization problem and is discussed in Section 6.4.8.

### *Margins*

The sum of product and by-product revenues minus raw material costs is known as the gross margin (or sometimes product margin or just margin).

$$\text{Gross margin} = \text{Revenues} - \text{Raw materials costs} \tag{6.1}$$

Gross margin is a useful concept, as raw materials costs are almost always the largest contributor to production costs (typically 80% to 90% of total cost of production). Raw materials and product prices of commodities are often subject to high variability and can be difficult to forecast, but margins suffer less variability if producers are able to pass feedstock price increases on to their customers. Margins are therefore often used in price forecasting, as described in Section 6.4.2.

**Table 6.1 Some Stoichiometric By-products**

| Feeds | Main Product | By-product |
|---|---|---|
| cumene + air | phenol | acetone |
| propylene + ethylbenzene + air | propylene oxide | styrene |
| ethylene + chlorine | vinyl chloride monomer | HCl |
| allyl chloride + HOCl + NaOH | epichlorohydrin | NaCl |
| methane + steam | hydrogen | carbon dioxide |
| glucose | ethanol (by fermentation) | carbon dioxide |
| acetone cyanohydrin + methanol + $H_2SO_4$ | methyl methacrylate | ammonium sulphate |
| sodium chloride + electricity | chlorine | sodium hydroxide |

Margins vary widely between different sectors of the chemical industry. For commodities such as bulk petrochemicals and fuels, margins are typically very low (less than 10% of revenues) and may even occasionally be negative. Commodity businesses are usually cyclical because of investment cycles and experience higher margins when supply is short, as described in Section 6.4. When a product is tightly regulated (making market entry difficult) or subject to patent protection, then margins can be much higher. For example, margins on food additives, pharmaceutical products and biomedical implants are typically more than 40% of revenues and often higher than 80% of revenues.

### *Profits*

The cash cost of production (CCOP) is the sum of the fixed and variable production costs:

$$\text{CCOP} = \text{VCOP} + \text{FCOP} \tag{6.2}$$

where

VCOP = sum of all the variable costs of production minus by-product revenues
FCOP = sum of all the fixed costs of production

The cash cost of production is the cost of making product, not including any return on the equity capital invested. By convention, by-product revenues are usually taken as a credit and included in the VCOP. This makes it easier to determine cost per kilogram of producing the main product.

The gross profit is:

$$\text{Gross profit} = \text{Main product revenues} - \text{CCOP} \tag{6.3}$$

Gross profit should not be confused with gross margin, as gross profit includes all the other variable costs in addition to raw materials, and also includes fixed costs.

The profit made by the plant is usually subject to taxation. Different tax codes apply in different countries and locations, and the taxable income may not be the full gross profit. Taxes are discussed in more detail in Section 6.5. The net profit (or cash flow after tax) is the amount left after taxes are paid:

$$\text{Net profit} = \text{gross profit} - \text{taxes} \tag{6.4}$$

The net profit from the project is the money that is available as a return on the initial investments. Methods for evaluating the economic performance of investments are introduced in Sections 6.6 and 6.7.

It is sometimes useful to calculate a total cost of production (TCOP), assuming that a plant generates a specified return on investment. In this case an annual capital charge (ACC) is added to the cash cost of production:

$$\text{TCOP} = \text{CCOP} + \text{ACC} \tag{6.5}$$

Methods for calculating the annual capital charge are discussed in Section 6.7.6.

## 6.2.6 CASH FLOWS AT THE END OF THE PROJECT

If a plant ceases operation or is "mothballed" (shut down on a semi-permanent basis) then the working capital is recovered, but must be reinvested if the plant is restarted. When a plant is shut down permanently then it can be sold in its entirety or else broken up and sold as scrap. There are several companies that specialize in buying and reselling second-hand plant, and advertisements for used plants and equipment can usually be found in the classified sections of the trade journals. The scrap value can be estimated based on the equipment weight and is usually less than 10% of the ISBL investment. OSBL investments are not recovered unless the entire site is shut down. If land was purchased for the plant, which is increasingly uncommon, then the land can be sold as an additional end of life credit. These cash flows at the end of the project are often not included in profitability analysis, as their timing is uncertain and they are often far enough in the future that they have negligible impact on any of the measures of profitability.

## 6.3 ESTIMATING CAPITAL COSTS

### 6.3.1 ACCURACY AND PURPOSE OF CAPITAL COST ESTIMATES

The accuracy of an estimate depends on the amount of design detail available, the accuracy of the cost data available, and the time spent on preparing the estimate. In the early stages of a project only an approximate estimate will be required, and justified, by the amount of information available.

The Association for the Advancement of Cost Estimating International (AACE International) is the professional association representing the cost engineering profession in the U.S.A. AACE International classifies capital cost estimates into five types according to their accuracy and purpose:

1. Order of magnitude estimates (“ballpark estimate”, “guesstimate” “Class 5 estimate”), accuracy typically ±30-50%, usually based on the costs of similar processes and requiring essentially no design information. These are used in initial feasibility studies and for screening purposes.
2. Preliminary (“approximate”, “study”, “feasibility”, “Class 4”) estimates, accuracy typically ±30%, which are used to make coarse choices between design alternatives. They are based on limited cost data and design detail.
3. Definitive (“authorization”, “budgeting”, “control”, “Class 3”) estimates, accuracy typically ±10-15%. These are used for the authorization of funds to proceed with the design to the point where an accurate and more detailed estimate can be made. Authorization may also include funds to cover cancellation charges on any long delivery equipment ordered at this stage of the design to avoid delay in the project. In a contracting organization this type of estimate could be used with a large contingency factor to obtain a price for tendering. Normally, however, an accuracy of about ±5% would be needed and a more detailed estimate would be made, if time permitted. With experience, and where a company has cost data available from similar projects, estimates of acceptable accuracy can be made at the flowsheet stage of the project. A rough P and I diagram and the approximate sizes of the major items of equipment would also be needed.
4. Detailed estimates (“quotation”, “tender”, “firm estimate”, “contractor’s estimate”, “Class 2 estimate”), accuracy ±5-10%, which are used for project cost control and estimates for fixed price contracts. These are based on the completed (or near complete) process design, firm quotes for equipment, and a detailed breakdown and estimation of the construction cost. By this stage the contractor can usually present a list of all the items that must be purchased and can make a firm commitment to the client.
5. Check estimates (“tender”, “as-bid”, “Class 1 estimate”), accuracy ±5-10%. This is based on a completed design and concluded negotiations on procurement of specialized items and long lead-time items.

The cost of preparing an estimate increases from about 0.1 per cent of the total project cost for ±30 per cent accuracy, to about 3 per cent for a detailed estimate with an accuracy of ±5%.

As a project proceeds from initial concept through detailed design to start-up, costs begin to be accumulated, particularly once procurement and construction get underway (Figure 6.1*a*). At the same time, the ability of the design engineer to influence project cost decreases, and is minimal by the time construction begins (Figure 6.1*b*). There is therefore a strong incentive to try to estimate project costs at as early a stage as possible, even if the design information is incomplete, so that the project can be optimized, evaluated and abandoned if it is not attractive.

## 6.3.2 RAPID COST ESTIMATES

### *Historic cost data*

The quickest way to make an order-of-magnitude estimate of plant cost is to scale it from the known cost of an earlier plant that used the same technology or from published data. This requires no design information other than the production rate.

The capital cost of a plant is related to capacity by the equation

$$C_2 = C_1 \left(\frac{S_2}{S_1}\right)^n \tag{6.6}$$

where

$C_2$ = ISBL capital cost of the plant with capacity $S_2$,
$C_1$ = ISBL capital cost of the plant with capacity $S_1$.

The exponent $n$ is typically 0.8 to 0.9 for processes that use a lot of mechanical work or gas compression (e.g., methanol, paper pulping, solids handling plants). For typical petrochemical processes $n$ is usually about 0.7. For small-scale, highly instrumented processes $n$ is in the range 0.4 to 0.5. Averaged across

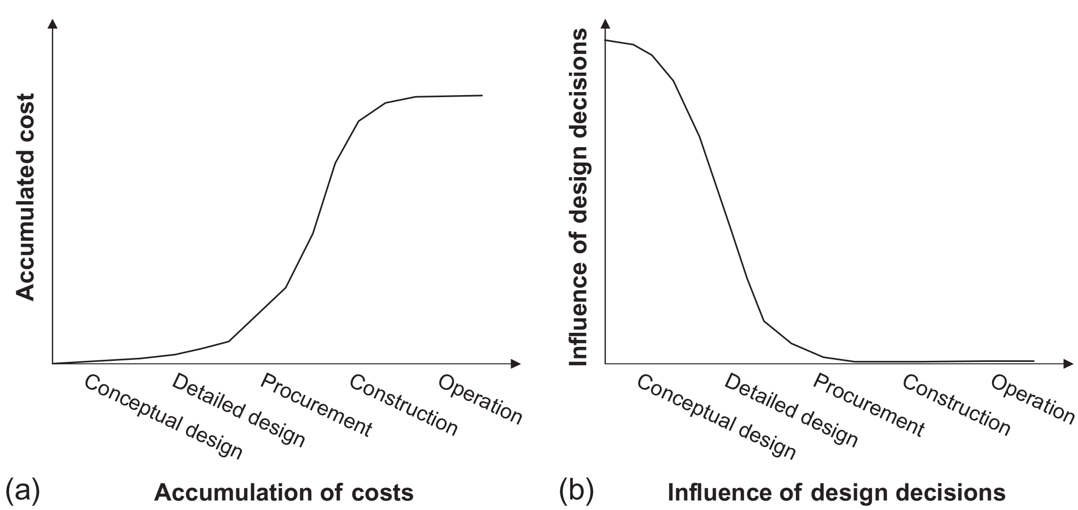


**FIGURE 6.1**

Influence of design decisions on project cost.

the whole chemical industry, $n$ is about 0.6, and hence equation 6.6 is commonly referred to as the "six-tenths rule". This value can be used to get a rough estimate of the capital cost if there are not sufficient data available to calculate the index for the particular process. Estrup (1972) gives a critical review of the six-tenths rule. Equation 6.6 is only an approximation, and if sufficient data are available the relationship is best represented on a log-log plot. Garrett (1989) has published capital cost-plant capacity curves for over 250 processes.

The journal *Hydrocarbon Processing* publishes supplements on refining, petrochemical and gas processing processes every other year. These supplements are available in print or CD format to subscribers and give approximate capital cost data for various licensed processes, which can be fitted using a rearranged form of equation 6.6:

$$C_2 = \frac{C_1}{S_1^n} \times S_2^n = aS_2^n \tag{6.7}$$

Values of the parameters $a$ and $n$ for some fuels and commodity chemical processes are given in Table 6.2. The costs in the *Hydrocarbon Processing* supplements are supplied by the technology vendors and are suitable for ballpark estimates only.

### Step count method

If cost data for a similar process is not available then an order-of-magnitude estimate can sometimes be made by adding contributions for different plant sections or functional units.

Experienced design engineers can often figure out costs of plant sections from historic total plant costs. For example, in many petrochemical processes roughly 20% of ISBL capital cost is in the reactor section and 80% is in the distillation and product purification sections.

An alternative approach is Bridgewater's method, which correlates plant cost against number of processing steps (Bridgewater and Mumford, 1979). For plants primarily processing liquids and solids:

$$Q \geq 60{,}000: \quad C = 3200N\left(\frac{Q}{s}\right)^{0.675} \tag{6.8}$$

$$Q < 60{,}000: \quad C = 280{,}000N\left(\frac{Q}{s}\right)^{0.3} \tag{6.9}$$

where:

$C$ = ISBL capital cost in U.S. \$, U.S. Gulf Coast, 2000 basis
$Q$ = plant capacity in metric tons per year
$s$ = reactor conversion (= mass of desired product per mass fed to the reactor)
$N$ = number of functional units.

(Note: the correlations have been updated from the original reference.)

A functional unit includes all the equipment and ancillaries needed for a significant process step or function, such as a reaction, separation or other major unit operation. Pumping and heat exchange are not normally considered as functional units unless they have substantial cost, for example, compressors, refrigeration systems or process furnaces.

**Table 6.2 Process cost correlations**

| Process | Licensor | Capacity units | $S_{lower}$ | $S_{upper}$ | *a* | *n* |
|---|---|---|---|---|---|---|
| ABS Resin (15% Rubber) by emulsion polymerization | Generic | MMlb/y | 50 | 300 | 12.146 | 0.6 |
| Acetic Acid by Cativa process | BP | MMlb/y | 500 | 2,000 | 3.474 | 0.6 |
| Acetic Acid by Low Water Methanol Carbonylation | Celanese | MMlb/y | 500 | 2,000 | 2.772 | 0.6 |
| Acrolein by propylene oxidation with Bi/Mo catalyst | Generic | MMlb/y | 30 | 150 | 6.809 | 0.6 |
| Adipic acid from phenol | Generic | MMlb/y | 300 | 1000 | 3.533 | 0.6 |
| Alkylation (sulphuric acid effluent refrigeration process) | Stratco/ DuPont | bpd | 4,000 | 20,000 | 0.160 | 0.6 |
| Alkylation (HF process) | UOP | bpd | 5,000 | 12,000 | 0.153 | 0.6 |
| Allyl chloride by propylene chlorination | Generic | MMlb/y | 80 | 250 | 7.581 | 0.6 |
| Alpha olefins (full range process) | Chevron Phillips | MMlb/y | 400 | 1,200 | 5.240 | 0.6 |
| Alpha olefins (full range process) | Shell | MMlb/y | 400 | 1,000 | 8.146 | 0.6 |
| Benzene by Sulpholane extraction | UOP/Shell | MMgal/y | 50 | 200 | 7.793 | 0.6 |
| Benzene by toluene hydrodealkylation | Generic | MMgal/y | 50 | 200 | 7.002 | 0.6 |
| Benzene reduction by Bensat | UOP | bpd | 8,000 | 15,000 | 0.0275 | 0.6 |
| Biodiesel (FAME) from vegetable oil | Generic | MMlb/y | 100 | 500 | 2.747 | 0.6 |
| bis-HET by Eastman Glycolysis | Eastman | MMlb/y | 50 | 200 | 0.500 | 0.6 |
| BTX Aromatics by Cyclar process | BP/UOP | tpy | 200,000 | 800,000 | 0.044 | 0.6 |
| BTX Aromatics by CCR Platforming | UOP | tpy | 200,000 | 800,000 | 0.015 | 0.6 |
| Butadiene by extractive distillation | UOP/BASF | MMlb/y | 100 | 500 | 5.514 | 0.6 |
| Butadiene by Oxo-D plus extractive distillation | Texas Petrochem. | MMlb/y | 100 | 500 | 11.314 | 0.6 |
| Butene-1 by Alphabutol ethylene dimerization | Axens | tpy | 5,000 | 30,000 | 0.0251 | 0.6 |
| Butene-1 by BP Process | BP | tpy | 20,000 | 80,000 | 0.169 | 0.6 |
| Caprolactam from nitration-grade toluene | SNIA BPD S. p.A. | tpy | 40,000 | 120,000 | 0.321 | 0.6 |
| Carbon monoxide by steam methane reforming | Generic | MMscf/y | 2,000 | 6,000 | 0.363 | 0.6 |
| Catalytic Condensation for Gasoline Production | UOP | bpd | 10,000 | 30,000 | 0.222 | 0.6 |
| Catalytic reforming by CCR Platforming | UOP | bpd | 15,000 | 60,000 | 0.179 | 0.6 |
| Coking by Flexicoking including Fluid Coking | ExxonMobil | bpd | 15,000 | 40,000 | 0.343 | 0.6 |
| Coking by Selective Yield Delayed Coking | Foster Wheeler/UOP | bpd | 15,000 | 60,000 | 0.109 | 0.68 |
| Copolymer polypropylene by INNOVENE | BP | MMlb/y | 300 | 900 | 3.430 | 0.6 |

**Table 6.2 Process cost correlations—cont'd**

| Process | Licensor | Capacity units | $S_{lower}$ | $S_{upper}$ | *a* | *n* |
|---|---|---|---|---|---|---|
| Copolymer polypropylene by Unipol | Dow | MMlb/y | 300 | 900 | 3.641 | 0.6 |
| Copolymer polypropylene by SPHERIPOL Bulk | Basell | MMlb/y | 300 | 900 | 3.649 | 0.6 |
| Copolymer polypropylene by BORSTAR | Borealis | MMlb/y | 300 | 900 | 4.015 | 0.6 |
| Crude distillation by D2000 | TOTAL/ Technip | bpd | 150,000 | 300,000 | 0.151 | 0.6 |
| Cumene by Q-Max | UOP | tpy | 150,000 | 450,000 | 0.0120 | 0.6 |
| Cyclic Olefin Copolymer by Mitsui Process | Mitsui | MMlb/y | 60 | 120 | 12.243 | 0.6 |
| Cyclohexane by liq-phase hydrogenation of benzene | Axens | tpy | 100,000 | 300,000 | 0.0061 | 0.6 |
| Dewaxing by ISODEWAXING | Chevron Lummus | bpd | 6,000 | 15,000 | 0.256 | 0.6 |
| 2,6-Dimethylnaphthalene by MeOH alkylation | Exxon Mobil/ Kobe | MMlb/y | 50 | 100 | 7.712 | 0.6 |
| Dimethyl terephthalate by methanolysis | Generic | MMlb/y | 30 | 80 | 5.173 | 0.6 |
| Dimethyl terephthalate by Huels Oxidation | Huels | MMlb/y | 300 | 800 | 7.511 | 0.6 |
| Ethanol by ethylene hydration | Generic | Mgal/y | 30 | 90 | 9.643 | 0.6 |
| Ethanol (fuel grade) by Corn Dry Milling | Generic | tpy | 100,000 | 300,000 | 0.0865 | 0.6 |
| Ethylbenzene by EBOne | ABB Lummus/UOP | tpy | 300,000 | 700,000 | 0.0085 | 0.6 |
| Ethylene by ethane cracking | Generic | MMlb/y | 500 | 2,000 | 9.574 | 0.6 |
| Ethylene by UOP Hydro MTO | UOP/Norsk Hydro | MMlb/y | 500 | 2,000 | 8.632 | 0.6 |
| Ethylene: light naphtha cracker (max ethylene) | Generic | MMlb/y | 1,000 | 2,000 | 16.411 | 0.6 |
| Ethylene by ethane/propane cracker | Generic | MMlb/y | 1,000 | 2,000 | 7.878 | 0.6 |
| Ethylene by gas oil cracker | Generic | MMlb/y | 1,000 | 2,000 | 17.117 | 0.6 |
| Ethylene glycol via ethylene oxide hydrolysis | Shell | MMlb/y | 500 | 1,000 | 5.792 | 0.6 |
| Expandable polystyrene by suspension process | Generic | MMlb/y | 50 | 100 | 3.466 | 0.6 |
| Fischer Tropsch Process | ExxonMobil | tpy | 200,000 | 700,000 | 0.476 | 0.6 |
| Fluid catalytic cracking | KBR | bpd | 20,000 | 60,000 | 0.210 | 0.6 |
| Fluid catalytic cracking with power recovery | UOP | bpd | 20,000 | 60,000 | 0.302 | 0.6 |
| Gas to liquids by Syntroleum Process | Syntroleum | bpd | 30,000 | 100,000 | 2.279 | 0.6 |
| Gas sweetening by Amine Guard FS to pipeline spec | UOP | MMscf/d | 300 | 800 | 0.386 | 0.6 |
| Gasification by GE Gasification Process Maya crude | GE Energy | bpd | 7,000 | 15,000 | 0.681 | 0.6 |

*Continued*

**Table 6.2 Process cost correlations—cont'd**

| Process | Licensor | Capacity units | $S_{lower}$ | $S_{upper}$ | *a* | *n* |
|---|---|---|---|---|---|---|
| Gasoline desulphurization, ultra-deep by Prime-G+ | Axens | bpd | 7,000 | 15,000 | 0.0420 | 0.58 |
| Glucose (40% Solution) by basic wet corn milling | Generic | MMlb/y | 300 | 800 | 3.317 | 0.6 |
| HDPE Pellets by BP Gas Phase Process | BP Amoco | MMlb/y | 300 | 700 | 3.624 | 0.6 |
| HDPE Pellets by Phillips Slurry Process | Phillips | MMlb/y | 300 | 700 | 3.370 | 0.6 |
| HDPE Pellets by Zeigler Slurry Process | Zeigler | MMlb/y | 300 | 700 | 4.488 | 0.6 |
| High impact polystyrene by bulk polymerization | Dow | MMlb/y | 70 | 160 | 2.970 | 0.6 |
| Hydrocracking by ISOCRACKING | Chevron Lummus | bpd | 20,000 | 45,000 | 0.221 | 0.6 |
| Hydrocracking by Unicracking, distillate | UOP | bpd | 20,000 | 45,000 | 0.136 | 0.66 |
| Hydrocracking | Axens | bpd | 20,000 | 45,000 | 0.198 | 0.6 |
| Hydrogen by steam methane reforming | Foster Wheeler | MMscf/d | 10 | 50 | 1.759 | 0.79 |
| Hydrotreating by Unionfining | UOP | bpd | 10,000 | 40,000 | 0.0532 | 0.68 |
| Isomerization by Once-through Penex | UOP | bpd | 8,000 | 15,000 | 0.0454 | 0.6 |
| Isomerization by Penex-Molex | UOP | bpd | 8,000 | 15,000 | 0.120 | 0.6 |
| Isophthalic acid by m-Xylene oxidation | Generic | MMlb/y | 160 | 300 | 9.914 | 0.6 |
| Isoprene via isobutylene carbonylation | IFP | MMlb/y | 60 | 200 | 10.024 | 0.6 |
| Isoprene by propylene dimerization and pyrolysis | Generic | MMlb/y | 60 | 200 | 6.519 | 0.6 |
| Linear alkylbenzene by PACOL/ DeFine/PEP/Detal | UOP | MMlb/y | 100 | 250 | 4.896 | 0.6 |
| Linear alpha olefins | Chevron | MMlb/y | 300 | 700 | 5.198 | 0.6 |
| Linear alpha olefins by Linear-1 | UOP | tpy | 200,000 | 300,000 | 0.122 | 0.6 |
| Maleic anhydride by fluid bed process | Generic | MMlb/y | 70 | 150 | 7.957 | 0.6 |
| Methacrylic acid by isobutylene oxidation | Generic | MMlb/y | 70 | 150 | 7.691 | 0.6 |
| Methanol via steam reforming & synthesis | Davy Process Tech. | tpd | 3,000 | 7,000 | 2.775 | 0.6 |
| m-Xylene by MX Sorbex | UOP | MMlb/y | 150 | 300 | 4.326 | 0.6 |
| Naphthalene by 3-stage fractional crystallizer | Generic | MMlb/y | 20 | 50 | 2.375 | 0.6 |
| N-Butanol from crude C4s | BASF | MMlb/y | 150 | 300 | 8.236 | 0.6 |
| Norbornene by Diels-Alder reaction | Generic | MMlb/y | 40 | 90 | 7.482 | 0.6 |
| Pentaerythritol by condensation | Generic | MMlb/y | 40 | 90 | 6.220 | 0.6 |

**Table 6.2 Process cost correlations—cont'd**

| Process | Licensor | Capacity units | $S_{lower}$ | $S_{upper}$ | *a* | *n* |
|---|---|---|---|---|---|---|
| PET resin chip with comonomer by NG3 | DuPont | MMlb/y | 150 | 300 | 4.755 | 0.6 |
| Phenol from cumene (zeolite catalyst) | UOP/ABB Lummus | MMlb/y | 200 | 600 | 6.192 | 0.6 |
| Phthalic anhydride by catalytic oxidation | Generic | MMlb/y | 100 | 200 | 7.203 | 0.6 |
| Polycarbonate by interfacial polymerization | Generic | MMlb/y | 70 | 150 | 20.680 | 0.6 |
| Polyethylene terephthalate (melt phase) | Generic | MMlb/y | 70 | 200 | 5.389 | 0.6 |
| Polystyrene by bulk polymerization, plug flow | Generic | MMlb/y | 70 | 200 | 2.551 | 0.6 |
| Propylene by Oleflex | UOP | tpy | 150,000 | 350,000 | 0.0943 | 0.6 |
| Propylene by metathesis | Generic | MMlb/y | 500 | 1,000 | 1.899 | 0.6 |
| Purified terphthalic acid | EniChem/ Technimont | MMlb/y | 350 | 700 | 10.599 | 0.6 |
| p-Xylene by Isomar and Parex | UOP | tpy | 300,000 | 700,000 | 0.0230 | 0.6 |
| p-Xylene by Tatoray Process | UOP | bpd | 12,000 | 20,000 | 0.0690 | 0.6 |
| Refined Glycerine by distillation/ adsorption | Generic | MMlb/y | 30 | 60 | 2.878 | 0.6 |
| Sebaccic Acid by cyclododecanone route | Sumitomo | MMlb/y | 8 | 16 | 13.445 | 0.6 |
| Sorbitol (70%) by continuous hydrogenation | Generic | MMlb/y | 50 | 120 | 4.444 | 0.6 |
| Styrene by SMART | ABB Lummus/UOP | tpy | 300,000 | 700,000 | 0.0355 | 0.6 |
| Vinyl acetate by Cativa Integrated Process | BP | MMlb/y | 300 | 800 | 7.597 | 0.6 |
| Vinyl acetate by Celanese VAntage Process | Celanese | MMlb/y | 300 | 800 | 6.647 | 0.6 |
| Visbreaking by coil-type visbreaker | Foster Wheeler/UOP | bpd | 6,000 | 15,000 | 0.278 | 0.48 |

*Note*

1. *Values of* a *are in January 2006 million US$ on a U.S. Gulf Coast (USGC) basis (Nelson Farrar index = 1961.6, CE index = 478.6).*
2. *$S_{lower}$ and $S_{upper}$ indicate the bounds of the region over which the correlation can be applied.*
3. *S is based on product rate for chemicals, feed rate for fuels.*
4. *If the index* n *is 0.6 then the correlation is an extrapolation around a single cost point.*
5. *Flow units are: MMlb/y = million pounds per year; tpy = short tons per year; bpd = barrels per day.*
6. *Correlations are based on data taken from Hydrocarbon Processing (2003, 2004a and 2004b), except where the licensor is stated as "Generic", in which cases the correlations are based on data from Nexant PERP reports (see www.Nexant.com/products for a full list of reports available).*

### *Manufactured products*

Step-count methods such as Bridgewater's method were developed for chemical plants and do not extend well to other types of manufacturing. For large-scale production of manufactured items (>500,000 pieces per year) a rule of thumb is:

$$\text{TCOP} = 2 \times \text{materials cost} \tag{6.10}$$

This equation can be used to make a very approximate estimate of plant cost if fixed costs and utilities can be estimated.

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## EXAMPLE 6.1

The process for making cyclohexane by saturation of benzene consists of a feed-effluent heat exchanger, a saturation reactor and a product stabilizer column. Estimate the cost of a plant that produces 200,000 metric tons per year (200 kte/y) of cyclohexane using the correlation in Table 6.2 and Bridgewater's method.

### Solution

From Table 6.2, the cost correlation for the Axens process for benzene saturation gives:

$$\begin{aligned} C &= 0.0061\,(S)^{0.6} \\ &= 0.0061\,\left(2 \times 10^5\right)^{0.6} \\ &= \underline{\underline{\$9.2\text{MM}}} \text{ expressed on a Jan. 2006 USGC basis.} \end{aligned}$$

Using Bridgewater's method, we have two functional units (the reactor and product stabilizer – the heat exchanger doesn't count) and assuming that the reactor conversion is 1.0, we can substitute into equation 6.8:

$$\begin{aligned} C &= 3200 \times 2 \times (Q)^{0.675} \\ &= 3200 \times 2 \times \left(2 \times 10^5\right)^{0.675} \\ &= \underline{\underline{\$24\text{ MM}}} \text{ expressed on a 2000 USGC basis.} \end{aligned}$$

Note that we have obtained two very different answers. Bridgewater's correlation is known to be only an approximation; however, Table 6.2 is based on data from technology vendors that may be somewhat understated. With the level of information available it is probably safe to say that the cost is in the range \$10 MM to \$20 MM. Note also that the costs are not on the same time basis. Methods for correcting costs on different time bases will be discussed in Section 6.3.5, below.

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## 6.3.3 THE FACTORIAL METHOD OF COST ESTIMATION

Capital cost estimates for chemical process plants are often based on an estimate of the purchase cost of the major equipment items required for the process, the other costs being estimated as factors of the equipment cost. The accuracy of this type of estimate will depend on what stage the design has reached at the time the estimate is made, and on the reliability of the data available on equipment costs. In the later stages of the project design, when detailed equipment specifications are available and firm quotes have been obtained from vendors, a relatively accurate estimate of the capital cost of the project can be made by this method.

### *Lang factors*

Lang (1948) proposed that the ISBL fixed capital cost of a plant is given as a function of the total purchased equipment cost by the equation:

$$C = F\left(\sum C_e\right) \tag{6.11}$$

where:

$C$ = total plant ISBL capital cost (including engineering costs)
$\Sigma C_e$ = total delivered cost of all the major equipment items: reactors, tanks, columns, heat exchangers, furnaces, etc.
$F$ = an installation factor, later widely known as a Lang factor.

Lang originally proposed the following values of $F$, based on 1940s economics:

$F = 3.1$ for solids processing plant
$F = 4.74$ for fluids processing plant
$F = 3.63$ for mixed fluids-solids processing plant

Hand (1958) suggested that better results are obtained by using different factors for different types of equipment. Examples of the factors proposed by Hand are given in Table 6.3. Hand also observed that this approach should only be used in the earliest stages of process design and in the absence of detailed design information.

Both Lang (1948) and Hand (1958) included home office costs but not offsite costs or contingency in their installation factors, so beware of double counting Engineering Procurement and Construction (EPC) costs when using this approach. The relative costs of materials and labour have changed substantially from when these factors were developed, and the accuracy of the correlation probably never warranted three significant figures for $F$. Most practitioners using this method therefore use a Lang factor of 3, 4 or 5, depending on the plant scale (larger plant = smaller factor) and type.

### Detailed factorial estimates

Equation 6.11 can be used to make a preliminary estimate once the flowsheet has been drawn up and the main plant equipment has been sized. When more detailed design information is available then the installation factor can be estimated somewhat more rigorously, by considering the cost factors that are compounded into the Lang factor individually.

The direct-cost items that are incurred in the construction of a plant, in addition to the cost of equipment are:

1. Equipment erection, including foundations and minor structural work.
2. Piping, including insulation and painting.
3. Electrical, power and lighting.

**Table 6.3 Installation factors proposed by Hand (1958)**

| Equipment type | Installation factor |
|---|---|
| Compressors | 2.5 |
| Distillation columns | 4 |
| Fired heaters | 2 |
| Heat exchangers | 3.5 |
| Instruments | 4 |
| Miscellaneous equipment | 2.5 |
| Pressure vessels | 4 |
| Pumps | 4 |

4. Instruments and automatic process control (APC) systems.
5. Process buildings and structures.
6. Ancillary buildings, offices, laboratory buildings, workshops.
7. Storage for raw materials and finished product.
8. Utilities (Services), provision of plant for steam, water, air, fire fighting services (if not costed separately as offsites).
9. Site preparation.

The contribution of each of these items to the total capital cost is calculated by multiplying the total purchased equipment cost by an appropriate factor. As with the basic Lang factor, these factors are best derived from historical cost data for similar processes. Typical values for the factors are given in several references, Happle and Jordan (1975) and Garrett (1989). Guthrie (1974) splits the costs into the material and labour portions and gives separate factors for each.

The accuracy and reliability of an estimate can be improved by dividing the process into sub-units and using factors that depend on the function of the sub-units; see Guthrie (1969). In Guthrie's detailed method of cost estimation the installation, piping and instrumentation costs for each piece of equipment are costed separately. Detailed costing is only justified if the cost data available are reliable and the design has been taken to the point where all the cost items can be identified and included. Gerrard (2000) gives factors for individual pieces of equipment as a function of equipment cost and complexity of installation.

Typical factors for the components of the capital cost are given in Table 6.4. These can be used to make an approximate estimate of capital cost using equipment cost data published in the literature.

**Table 6.4 Typical factors for estimation of project fixed capital cost**

| | Process type | | |
|---|---|---|---|
| **Item** | **Fluids** | **Fluids – solids** | **Solids** |
| 1. Major equipment, total purchase cost | $C_e$ | $C_e$ | $C_e$ |
| $f_{er}$ Equipment erection | 0.3 | 0.5 | 0.6 |
| $f_p$ Piping | 0.8 | 0.6 | 0.2 |
| $f_i$ Instrumentation and control | 0.3 | 0.3 | 0.2 |
| $f_{el}$ Electrical | 0.2 | 0.2 | 0.15 |
| $f_c$ Civil | 0.3 | 0.3 | 0.2 |
| $f_s$ Structures and buildings | 0.2 | 0.2 | 0.1 |
| $f_l$ Lagging and paint | 0.1 | 0.1 | 0.05 |
| ISBL cost, $C = \Sigma C_e \times$ | 3.3 | 3.2 | 2.5 |
| Offsites (OS) | 0.3 | 0.4 | 0.4 |
| Design and Engineering (D&E) | 0.3 | 0.25 | 0.2 |
| Contingency (X) | 0.1 | 0.1 | 0.1 |
| Total fixed capital cost $C_{FC} = C\,(1 + \text{OS})(1 + \text{D\&E} + \text{X})$ | | | |
| $= C \times$ | 1.82 | 1.89 | 1.82 |
| $= \Sigma C_e \times$ | 6.00 | 6.05 | 4.55 |

The installation factors given in Tables 6.3 and 6.4 are for plants built from carbon steel. When more exotic materials are used then a materials factor $f_m$ should also be introduced:

$$f_m = \frac{\text{purchased cost of item in exotic material}}{\text{purchased cost of item in carbon steel}} \tag{6.12}$$

Note that $f_m$ is not equal to the ratio of the metal prices, as the equipment purchased cost also includes labour costs, overheads, fabricator's profit and other costs that do not scale directly with metal price. Equation 6.11 can then be expanded for each piece of equipment to give:

$$C = \sum_{i=1}^{i=M} C_{e,i,CS} \left[(1+f_p)f_m + (f_{er}+f_{el}+f_i+f_c+f_s+f_l)\right] \tag{6.13}$$

or

$$C = \sum_{i=1}^{i=M} C_{e,i,A} \left[(1+f_p) + (f_{er}+f_{el}+f_i+f_c+f_s+f_l)/f_m\right] \tag{6.14}$$

where:

$C_{e,i,CS}$ = purchased equipment cost of equipment $i$ in carbon steel
$C_{e,i,A}$ = purchased equipment cost of equipment $i$ in alloy
$M$ = total number of pieces of equipment
$f_p$ = installation factor for piping
$f_{er}$ = installation factor for equipment erection
$f_{el}$ = installation factor for electrical work
$f_i$ = installation factor for instrumentation and process control
$f_c$ = installation factor for civil engineering work
$f_s$ = installation factor for structures and buildings
$f_l$ = installation factor for lagging, insulation or paint

Failure to properly correct installation factors for materials of construction is one of the most common sources of error with the factorial method. Typical values of the materials factor for common engineering alloys are given in Table 6.5.

**Table 6.5 Materials cost factors, $f_m$, relative to plain carbon steel.**

| Material | $f_m$ |
|---|---|
| Carbon steel | 1.0 |
| Aluminum and bronze | 1.07 |
| Cast steel | 1.1 |
| 304 stainless steel | 1.3 |
| 316 stainless steel | 1.3 |
| 321 stainless steel | 1.5 |
| Hastelloy C | 1.55 |
| Monel | 1.65 |
| Nickel and Inconel | 1.7 |

### *Summary of the factorial method*

Many variations on the factorial method are used. The method outlined below can be used with the data given in this chapter to make a quick, approximate estimate of the fixed capital investment needed for a project.

1. Prepare material and energy balances; draw up preliminary flow-sheets; size major equipment items and select materials of construction.
2. Estimate the purchased cost of the major equipment items. See next section.
3. Calculate the ISBL installed capital cost, using the factors given in Table 6.4 and correcting for materials of construction using equation 6.13 or 6.14 with the materials factors given in Table 6.5.
4. Calculate the OSBL, engineering and contingency costs using the factors given in Table 6.4.
5. The sum of ISBL, OSBL, engineering and contingency costs is the fixed capital investment.
6. Estimate the working capital as a percentage of the fixed capital investment; 10 to 20 per cent is typical (or better, calculate it from the cost of production if this has been estimated – see Section 6.4).
7. Add the fixed and working capital to get the total investment required.

## 6.3.4 ESTIMATING PURCHASED EQUIPMENT COSTS

The factorial method of cost estimation is based on purchased equipment costs and therefore requires good estimates for equipment costs. Costs of single pieces of equipment are also often needed for minor revamp and de-bottlenecking projects.

The best source of purchased equipment costs is recent data on actual prices paid for similar equipment. Engineers working for Engineering, Procurement and Construction (EPC) companies (often referred to as Contractors) have access to large amounts of high quality data, as these companies carry out many projects globally every year. Engineers working in operating companies may have access to data from recent projects, but unless they work for a large company that carries out many capital projects they are unlikely to be able to develop and maintain current cost correlations for more than a few basic equipment types. Most large companies recognize the difficulty of making reliable cost estimates and employ a few experienced cost engineering specialists who collect data and work closely with the EPC companies on project budgets.

Actual prices paid for equipment and bulk items may differ substantially from catalogue or list prices, depending on the purchasing power of the contractor or client and the urgency of the project. Discounts and surcharges are highly confidential business information and will be closely guarded even within EPC companies.

Those design engineers who are outside the EPC sector and do not have the support of a cost estimating department must rely on cost data from the open literature or use cost estimating software. The most widely used software for estimating chemical plant costs is the Aspen Capital Cost Estimator™ (ACCE) suite of tools licensed by Aspen Technology Inc. The cost estimation software within ACCE is built on the ICARUS™ cost estimation algorithms. ACCE does not use the factorial method, but instead estimates equipment costs, bulk costs and installation costs from the costs of materials and labour, following the practice used by cost engineers for detailed estimating. The models in ACCE are developed by a team of cost engineers based on data collected from EPC companies and equipment manufacturers. The models are updated annually.

The ACCE software is included in the standard Aspen / Hsysys academic package and is available in most universities. Other commercial cost estimating programs are available and are gaining wider use, for example, Cost Engineering Consultancy licenses the Cleopatra Enterprise software. Cleopatra is designed to run from UniSim or Hysys process simulations and is based on cost data that are more accurate for Northwest Europe and Middle East projects. The correlations in Cleopatra are also built up from equipment, materials and installation costs collected by cost engineers. Both ACCE and Cleopatra can give reasonably good estimates when used properly and both are described in more detail in Section 6.3.8.

There is an abundance of equipment cost data and cost correlations in the open literature, but much of it is of very poor quality. The relationship between size and cost given in equations 6.6 and 6.7 can also be used for equipment if a suitable size parameter is used. If the size range spans several orders of magnitude, then log-log plots usually give a better representation of the relationship than simple equations.

Some of the most reliable information on equipment costs can be found in the professional cost engineering literature. Correlations based on recent data are occasionally published in *Cost Engineering*, which is the journal of the Association for the Advancement of Cost Engineering International (AACE International). AACE International also has an excellent web site, www.aacei.org, which has cost models that can be used by members. There is also an extensive listing of other web resources for cost estimating at www.aacei.org/resources. The U.K. Association of Cost Engineers (ACostE) publishes the journal *The Cost Engineer*, and also prints a guide to capital cost estimating (Gerrard, 2000), which gives cost curves for the main types of process equipment based on recent data. The prices are given in British pounds sterling on a U.K. basis, and are useful for making estimates of prices in Northwest Europe. The International Cost Engineering Council web site (www.icoste.org) provides links to 46 international cost engineering societies, several of which maintain databases of local costs.

Many cost correlations can be found in chemical engineering textbooks, for example Douglas (1988), Garrett (1989), Turton *et al.* (2012), Peters *et al.* (2003) and Ulrich and Vasudevan (2004). The references for such correlations should always be checked carefully. When they are properly referenced they are often found to be based on data published by Guthrie (1969, 1974) and updated using either cost indices (as described in Section 6.3.6) or a few recent data points. Guthrie's correlations were reasonably good when published, but there have been substantial changes in the relative contributions of material and fabrication costs of most process equipment since then. Academic authors usually do not have access to sufficient high quality cost data to be able to make reliable correlations, and most of the academic correlations predict lower costs than would be obtained using ACCE or other detailed estimating methods. These correlations are adequate for the purposes of university design projects but are not useful for assessing the costs of real projects. It is to be hoped that the authors of these publications will benchmark the correlations against ACCE or Cleopatra in future editions, which will improve the accuracy of the correlations and make them more useful to those who do not have access to costing software.

Detailed estimates are usually made by costing the materials and labour required for each item in the plant, making a full analysis of the work breakdown structure (WBS) to arrive at an accurate estimate of the labour. This method must be followed whenever cost or price data is not available, for example, when making an estimate of the cost of specialized equipment that cannot be found in the literature. For example, a reactor design is usually unique for a particular process but the design can be broken down into standard components (vessels, heat-exchange surfaces, spargers, agitators, etc.) the cost of which can be found in the literature and used to build up an estimate of the reactor cost. This method is described by Dysert (2007) and Woodward and Chen (2007) in sections of the AACE International training manual (Amos, 2011). Breakdowns of the materials and labour components for many types of process equipment are given by Page (1996). Pikulik and Diaz (1977) give a method of costing major equipment items from cost data on the basic components: shells, heads, nozzles, and internal fittings. Purohit (1983) gives a detailed procedure for estimating the cost of heat exchangers.

A large amount of vendor information is now available on-line and can easily be found using any of the major search engines or by starting from directories such as www.purchasing.com. On-line costs are usually manufacturer's catalogue prices for small-order quantities. Large order sizes (as filled by contractors) are often steeply discounted. Items requiring special fabrication, for example large vessels or compressors, may experience discounts or surcharges depending on the state of the manufacturer's order books and the purchasing power of the customer.

For those design engineers who lack access to reliable cost data or estimating software, the correlations given in Table 6.6 can be used for preliminary estimates. The correlations in Table 6.6 are of the form:

$$C_e = a + b\,S^n \tag{6.15}$$

where:

$C_e$ = purchased equipment cost on a U.S. Gulf Coast basis, Jan. 2007 (CE index (CEPCI) = 509.7, NF refinery inflation index = 2059.1)
$a$, $b$ = cost constants in Table 6.6
$S$ = size parameter, units given in Table 6.6
$n$ = exponent for that type of equipment

**Table 6.6 Purchased equipment cost for common plant equipment**

| Equipment | Units for size, S | S lower | S upper | a | b | n | Note |
|---|---|---|---|---|---|---|---|
| ***Agitators & mixers*** | | | | | | | |
| Propeller | driver power, kW | 5.0 | 75 | 15,000 | 990 | 1.05 | |
| Spiral ribbon mixer | driver power, kW | 5.0 | 35 | 27,000 | 110 | 2.0 | |
| Static mixer | Litres/s | 1.0 | 50 | 500 | 1,030 | 0.4 | |
| ***Boilers*** | | | | | | | |
| Packaged, 15 to 40 bar | kg/h steam | 5,000 | 200,000 | 106,000 | 8.7 | 1.0 | |
| Field erected, 10 to 70 bar | kg/h steam | 20,000 | 800,000 | 110,000 | 45 | 0.9 | |
| ***Centrifuges*** | | | | | | | |
| High speed disk | diameter, m | 0.26 | 0.49 | 50,000 | 423,000 | 0.7 | |
| Atmospheric suspended basket | power, kW | 2.0 | 20 | 57,000 | 660 | 1.5 | |

**Table 6.6 Purchased equipment cost for common plant equipment—cont'd**

| Equipment | Units for size, S | S lower | S upper | a | b | n | Note |
|---|---|---|---|---|---|---|---|
| ***Compressors*** | | | | | | | |
| Blower | m3/h | 200 | 5,000 | 3,800 | 49 | 0.8 | |
| Centrifugal | driver power, kW | 75 | 30,000 | 490,000 | 16,800 | 0.6 | |
| Reciprocating | driver power, kW | 93 | 16,800 | 220,000 | 2,300 | 0.75 | |
| ***Conveyors*** | | | | | | | |
| Belt, 0.5 m wide | length, m | 10 | 500 | 36,000 | 640 | 1.0 | |
| Belt, 1.0 m wide | length, m | 10 | 500 | 40,000 | 1,160 | 1.0 | |
| Bucket elevator, 0.5m bucket | height, m | 10 | 30 | 15,000 | 2,300 | 1.0 | |
| ***Crushers*** | | | | | | | |
| Reversible hammer mill | t/h | 30 | 400 | 60,000 | 640 | 1.0 | |
| Pulverisers | kg/h | 200 | 4,000 | 14,000 | 590 | 0.5 | |
| ***Crystallizers*** | | | | | | | |
| Scraped surface crystallizer | length, m | 7 | 280 | 8,400 | 11,300 | 0.8 | |
| ***Distillation columns*** | | | | | | | |
| See pressure vessels, packing and trays | | | | | | | |
| ***Dryers*** | | | | | | | |
| Direct contact Rotary | area, m2 | 11 | 180 | 13,000 | 9,100 | 0.9 | 1 |
| Atmospheric tray batch | area, m2 | 3.0 | 20 | 8,700 | 6,800 | 0.5 | 2 |
| Spray dryer | evap rate kg/h | 400 | 4,000 | 350,000 | 1,900 | 0.7 | |
| ***Evaporators*** | | | | | | | |
| Vertical tube | area, m2 | 11 | 640 | 280 | 30,500 | 0.55 | |
| Agitated Falling film | area, m2 | 0.5 | 12 | 75,000 | 56,000 | 0.75 | |
| ***Exchangers*** | | | | | | | |
| U-tube shell and tube | area, m2 | 10 | 1,000 | 24,000 | 46 | 1.2 | |
| Double pipe | area, m2 | 1.0 | 80 | 1,600 | 2,100 | 1.0 | |
| Thermosyphon reboiler | area, m2 | 10 | 500 | 26,000 | 104 | 1.1 | |
| U-tube Kettle reboiler | area, m2 | 10 | 500 | 25,000 | 340 | 0.9 | |
| Plate and frame | area, m2 | 1.0 | 500 | 1,350 | 180 | 0.95 | 3 |
| ***Filters*** | | | | | | | |
| Plate and frame | capacity, m3 | 0.4 | 1.4 | 110,000 | 77,000 | 0.5 | |
| Vacuum drum | area, m2 | 10 | 180 | -63,000 | 80,000 | 0.3 | |
| ***Furnaces*** | | | | | | | |
| Cylindrical | duty, MW | 0.2 | 60 | 68,500 | 93,000 | 0.8 | |
| Box | duty, MW | 30 | 120 | 37,000 | 95,000 | 0.8 | |
| ***Packings*** | | | | | | | |
| 304 ss Raschig rings | m3 | | | 0 | 7,300 | 1.0 | |
| Ceramic intalox saddles | m3 | | | 0 | 1,800 | 1.0 | |
| 304 ss Pall rings | m3 | | | 0 | 7,700 | 1.0 | |

Continued

**Table 6.6 Purchased equipment cost for common plant equipment—cont'd**

| Equipment | Units for size, S | S lower | S upper | a | b | n | Note |
|---|---|---|---|---|---|---|---|
| PVC structured packing | m3 | | | 0 | 500 | 1.0 | |
| 304 ss structured packing | m3 | | | 0 | 6,900 | 1.0 | 4 |
| ***Pressure vessels*** | | | | | | | |
| Vertical, cs | shell mass, kg | 160 | 250,000 | 10,000 | 29 | 0.85 | 5 |
| Horizontal, cs | shell mass, kg | 160 | 50,000 | 8,800 | 27 | 0.85 | |
| Vertical, 304 ss | shell mass, kg | 120 | 250,000 | 15,000 | 68 | 0.85 | 5 |
| Horizontal, 304 ss | shell mass, kg | 120 | 50,000 | 11,000 | 63 | 0.85 | |
| ***Pumps and drivers*** | | | | | | | |
| Single stage centrifugal | flow Litres/s | 0.2 | 126 | 6,900 | 206 | 0.9 | |
| Explosion proof motor | power, kW | 1.0 | 2,500 | -950 | 1,770 | 0.6 | |
| Condensing steam turbine | power, kW | 100 | 20,000 | -12,000 | 1,630 | 0.75 | |
| ***Reactors*** | | | | | | | |
| Jacketed, agitated | volume, m3 | 0.5 | 100 | 53,000 | 28,000 | 0.8 | 3 |
| Jacketed, agitated, glass lined | volume, m3 | 0.5 | 25 | 11,000 | 76,000 | 0.4 | |
| ***Tanks*** | | | | | | | |
| floating roof | capacity, m3 | 100 | 10,000 | 97,000 | 2,800 | 0.65 | |
| cone roof | capacity, m3 | 10 | 4,000 | 5,000 | 1,400 | 0.7 | |
| ***Trays*** | | | | | | | |
| Sieve trays | diameter, m | 0.5 | 5.0 | 110 | 380 | 1.8 | 6 |
| Valve trays | diameter, m | 0.5 | 5.0 | 180 | 340 | 1.9 | 6 |
| Bubble cap trays | diameter, m | 0.5 | 5.0 | 290 | 550 | 1.9 | 6 |
| ***Utilities*** | | | | | | | |
| Cooling tower & pumps | flow Litres/s | 100 | 10,000 | 150,000 | 1,300 | 0.9 | 7 |
| Packaged mechanical refrigerator | evaporator duty, kW | 50 | 1,500 | 21,000 | 3,100 | 0.9 | |
| Water ion exchange plant | flow m3/h | 1 | 50 | 12,000 | 5,400 | 0.75 | |

*Notes*

1. *Direct heated.*
2. *Gas fired.*
3. *Type 304 stainless steel.*
4. *With surface area 350 $m^2/m^3$.*
5. *Not including heads, ports, brackets, internals, etc. (see Chapter 13 for how to calculate wall thickness).*
6. *Cost per tray, based on a stack of 30 trays.*
7. *Field assembly.*
8. *All costs are U.S. Gulf Coast basis, Jan. 2007 (CE index (CEPCI) = 509.7, NF refinery inflation index = 2059.1).*

The correlations in Table 6.6 are only valid between the lower and upper values of $S$ indicated. The prices are all for carbon steel equipment except where noted in the table. Costs calculated from Table 6.6 can be updated and converted to international locations by following the methods set out in Sections 6.3.5 and 6.3.6.

## EXAMPLE 6.2

A plant modification has been proposed that will allow recovery of a by-product. The modification consists of adding the following equipment:

Distillation column, height 30m, diameter 3m, 50 sieve trays, operating pressure 10 bar
U-tube heat exchanger, area 60 $m^2$
Kettle reboiler, area 110 $m^2$
Horizontal pressure vessel, volume 3 $m^3$, operating pressure 10 bar
Storage tank, volume 50 $m^3$
Two centrifugal pumps, flow rate 3.6 $m^3$/h, driver power 500 W
Three centrifugal pumps, flow rate 2.5 $m^3$/h, driver power 1 kW (two installed plus one spare)

Estimate the installed ISBL capital cost of the modification if the plant is to be built from type 304 stainless steel. Estimate the cost using both Hand's method and the factors given in Table 6.4.

### Solution

The first step is to convert the units to those required for the correlations and determine any missing design information. The distillation column can be costed as a combination of a vertical pressure vessel and internals. For both pressure vessels we need to know the wall thickness. The details of how to calculate vessel wall thickness in accordance with the ASME Boiler and Pressure Vessel Code are given in Section 13.5, and the equation to use is equation 13.41.

The design pressure of the vessels should be 10% above the operating pressure (see Chapter 13), so the design pressure is 11 bar or roughly $1.1 \times 10^6$ N/$m^2$. The maximum allowable stress for type 304 stainless steel at 500 °F (260 °C) is 12.9 ksi or roughly 89 N/$mm^2$ (Table 13.2). Assuming the welds will be fully radiographed the weld efficiency is 1.0. Substituting in equation 13.41 for the column wall thickness, $t_w$, then gives:

$$t_w = \frac{1.1 \times 10^6 \times 3}{(2 \times 89 \times 10^6 \times 1.0) - (1.2 \times 1.1 \times 10^6)} \tag{13.41}$$

$$= 0.0187\,\text{m, say } 20\,\text{mm}.$$

We can now calculate the shell mass, using the density of 304 stainless steel (= 8000 kg/$m^3$, from Table 7.2).

$$\text{Shell mass} = \pi D_c L_c t_w \rho$$

where:
$D_c$ = vessel diameter, m
$L_c$ = vessel length, m
$t_w$ = wall thickness, m
$\rho$ = metal density, kg/$m^3$

So the shell mass for the distillation column is:

$$\text{Shell mass} = \pi \times 3.0 \times 30 \times 0.02 \times 8000 = 46685\,\text{kg}$$

For the horizontal pressure vessel we need to convert the volume into a length and diameter. Assuming that the vessel is a cylinder with $L_c = 2D_c$ then we can follow the same method as for the column and find $t_w$ = 8 mm and shell mass = 636 kg.

Using the correlations in Table 6.6, we obtain the following purchase costs for the stainless steel pressure vessels:
Distillation column shell, cost = 15,000 + 68 $(46685)^{0.85}$ = \$650,000
Horizontal pressure vessel, cost = 11,000 + 63 $(636)^{0.85}$ = \$26,000

For the remaining equipment we obtain the following purchase costs from the correlations in Table 6.6 based on carbon steel construction:
Distillation column trays, cost per tray = 110 + 380 $(3.0)^{1.8}$ = \$2855
Cost for 50 trays = \$143,000
U-tube heat exchanger, cost = 24,000 + 46 $(60)^{1.2}$ = \$30,300

Kettle reboiler, cost = 25,000 + 340 $(110)^{0.9}$ = \$48,400
Storage tank (conical head), cost = 5,000 + 1400 $(50)^{0.7}$ = \$27,000
Centrifugal pump, 3.6 $m^3/h$ = 1 L/s, so:
cost each = 6,900 + 206 $(1.0)^{0.9}$ = \$7100, cost for two pumps = \$14,200
driver (electric motor) cost each = −950 + 1770 $(0.5)^{0.6}$ = \$220
cost for two drivers = \$440
Centrifugal pump, 2.5 $m^3/h$ = 0.694 L/s, so:
cost each = 6,900 + 206 $(0.694)^{0.9}$ = \$7050, cost for three = \$21,100
driver (electric motor) cost each = −950 + 1770 $(1.0)^{0.6}$ = \$820
cost for three drivers = \$2,460

Note that the pumps and drivers are at the lower end of the range of validity of the cost correlations, but their costs are small compared to the other costs and the error introduced is therefore negligible given the overall accuracy of ± 30%.

Following Hand's method, the installed cost of the distillation column is then:

$$C = 4 \times 650{,}000 = \$2{,}600{,}000$$

The cost of the trays can be converted to type 304 stainless steel by multiplying by the appropriate materials factor from Table 6.5, giving:

$$C = 1.3 \times 143{,}000 = \$185{,}900$$

This then gives a total cost for the column plus internals of 2,600,000 + 185,900 = \$2,790,000.

The installed cost of the horizontal pressure vessel is 4 × 26,000 = \$104,000.

The installed cost for the exchangers and storage tank in carbon steel construction is:

$$C = 3.5\,(30{,}300 + 48{,}400) + 2.5\,(27{,}000) = \$343{,}000$$

so the cost in type 304 stainless steel is 1.3 × 343,000 = \$446,000.

For the pumps, we need to add the cost of the pump and driver before determining the installed cost. Only the cost of the pump needs to be converted to stainless steel. For the first set of pumps:

$$C = 4 \times (440 + (1.3 \times 14{,}200)) = \$75{,}600.$$

For the second set of pumps only two are installed (the other is a warehouse spare), so the total installed cost is:

$$C = (1.3 \times 7,050) + 820 + (4 \times 2 \times (820 + (1.3 \times 7,050))) = \$90{,}000.$$

The total installed ISBL cost of the plant is then:

$$C = 2,790,000 + 104,000 + 446,000 + 75,600 + 90,000 = \$3,506,000$$

or $\underline{\underline{\$3{:}5MM30 \pm \%}}$ within the accuracy of the method.

If instead we use the factors given in Table 6.4, then using equation 6.13, the installed cost for the exchangers, tank and pumps is equal to:

$$C = (30,300 + 48,400 + 27,000 + 14,200 + 14,100)[(1 + 0.8) \times 1.3 + (0.3 + 0.3 + 0.2 + 0.3 + 0.2 + 0.1)]$$
$$C = (134,000)[3.74] = \$501,200.$$

The installed cost for the pressure vessels and pump drivers (which do not require a materials conversion factor) is:

$$C = (650{,}000 + 26{,}000 + 440 + 1640)[1 + 0.8 + 0.3 + 0.3 + 0.2 + 0.3 + 0.2 + 0.1]$$
$$C = (678,080)[3.2] = \$2,170,000.$$

In addition to this, we require the cost of the trays in stainless steel and the cost of the spare pump and driver:

$$C = 820 + 1.3\,(185{,}900 + 7{,}050) = \$251{,}700.$$

The total installed ISBL cost of the plant is then:

$C = 501{,}200 + 2{,}170{,}00 + 251{,}700 = \$2{,}920{,}000$

or \$2.9 MM $\pm$ 30% within the accuracy of the method.

Note that although the answers obtained by the two methods are different, each is well within the range of accuracy of the other. Both estimates should be stated as being on a U.S. Gulf Coast basis, January 2007, as this is the basis for the correlations in Table 6.6.

## 6.3.5 COST ESCALATION

All cost-estimating methods use historical data, and are themselves forecasts of future costs. The prices of the materials of construction and the costs of labour are subject to inflation. Some method has to be used to update old cost data for use in estimating at the design stage, and to forecast the future construction cost of the plant.

The method usually used to update historical cost data makes use of published cost indices. These relate present costs to past costs, and are based on data for labour, material and energy costs published in government statistical digests.

$$\text{Cost in year A} = \text{Cost in year B} \times \frac{\text{Cost index in year A}}{\text{Cost index in year B}} \tag{6.16}$$

To get the best estimate, each job should be broken down into its components and separate indices should be used for labour and materials. It is often more convenient to use the composite indices published for various industries in the trade journals. These are weighted average indices combining the various components of costs in proportions considered typical for the particular industry.

In the United Kingdom, the two main cost indices are the ACE index published by the Association of Cost Engineers (ACostE) in *The Cost Engineer* and the PREDICT Plant Cost Index published in the journal *Process Engineering*. *Process Engineering* also publishes monthly cost indices for several countries, including the United States, United Kingdom, Japan, Australia and many of the EU countries.

A composite index for the United States process plant industry is published monthly in the journal *Chemical Engineering*; this is the Chemical Engineering Plant Cost Index (CEPCI), usually referred to as the CE index. *Chemical Engineering* also used to publish the Marshall and Swift index (M&S equipment cost index), but since 2010 that index has been discontinued.

For oil refinery and petrochemicals projects, the *Oil and Gas Journal* used to publish the Nelson-Farrar Refinery Construction Index (NF index). The index is now available as a subscription service from https://nelson-farrar-index.com//. The index is updated monthly and indices for forty types of equipment are updated quarterly. The Nelson-Farrar index is on a U.S. Gulf Coast basis rather than U.S. average, and is more reliable than the CE index for the types of equipment used in hydrocarbon processing.

The journal *Engineering News Record* publishes a monthly construction cost index. This is based on civil engineering projects and is sometimes used for updating offsites costs. This index has been published since 1904 and is the oldest of all the indices.

All cost indices should be used with caution and judgment. They do not necessarily relate the true make-up of costs for any particular piece of equipment or plant, nor the effect of supply and demand on prices. The longer the period over which the correlation is made the more unreliable the estimate.

Between 1970 and 1990 prices rose dramatically. Prices then grew at a more or less steady 2 to 3% per year until 2003, when high demand for fuels projects and high energy prices caused another period of steeper price inflation. Since the recession of 2009, The NF index has grown more steadily, while the CE index has been almost constant, probably reflecting the different contribution of different types of equipment to the two indices. The major cost indices for the U.S.A. are plotted in figure 6.2a. Figure 6.2b shows the same data plotted relative to the 1990 value of each index.

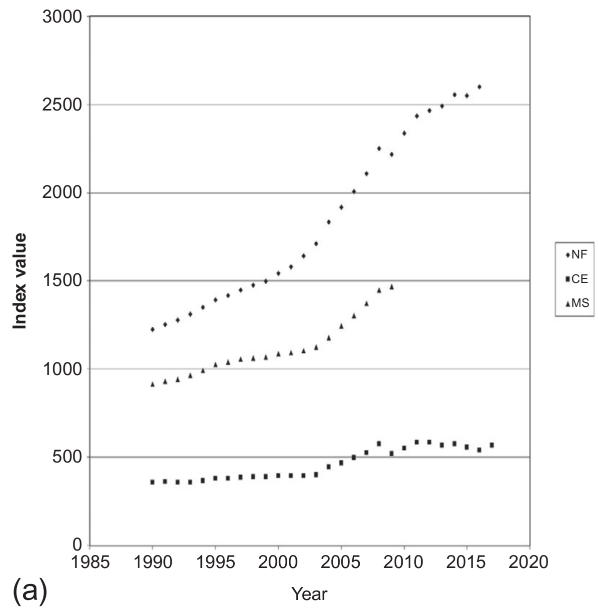



**FIGURE 6.2A**

Variation of major cost indices.

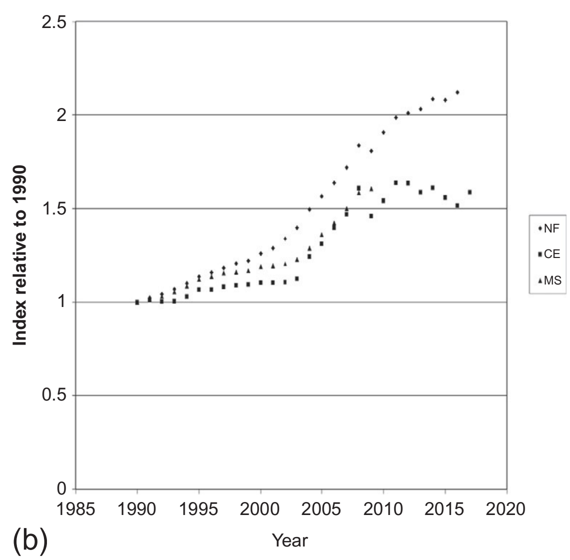



**FIGURE 6.2B**

Variation of major cost indices relative to 1990 = 1.0.

To estimate the future cost of a plant, some prediction has to be made of the future annual rate of inflation. This can be based on the extrapolation of one of the published indices, tempered by the engineer's own assessment of what the future may hold. Inflation is difficult to forecast, and allowance for inflation is often included in the contingency charges added to the project cost.

The time basis of a cost estimate is sometimes identified by writing the year as a subscript to the currency; for example $\$_{2004}$ or $€_{2008}$.

### EXAMPLE 6.3

The purchased cost of a shell and tube heat exchanger, carbon shell, 316 stainless steel tubes, heat transfer area 500 $m^2$, was \$64,000 in January 2003; estimate the cost in January 2018. Use the CEPCI Equipment Cost Index.

#### Solution

From Figure 6.2a (or by looking up the index in *Chemical Engineering*):

Index in 2003 = 402
Index in January 2018 = 576.4

So, estimated cost in January 2018 = \$64,000 × 576.4/402 = <u>\$92,000</u>.

## 6.3.6 LOCATION FACTORS

Most plant and equipment cost data is given on a U.S. Gulf Coast (USGC) or Northwest Europe (NWE) basis, as these are historically the main centres of the chemical industry, for which the most data are available. The cost of building a plant in any other location will depend on:

- Local fabrication and construction infrastructure
- Local labour availability and cost
- Costs of shipping or transporting equipment to site
- Import duties or other local tariffs
- Currency exchange rates, which affect the relative cost of locally purchased items such as bulk materials, when converted to a conventional pricing basis such as Euros or U.S. dollars.

These differences are often captured in cost estimating by using a location factor:

$$\text{Cost of plant in location A} = \text{cost of plant on USGC} \times LF_A \tag{6.17}$$

where: $LF_A$ = location factor for location A relative to USGC basis.

Location factors for international locations are a strong function of currency exchange rates and hence fluctuate with time. Cran (1976*a,b*), Bridgewater (1979), Soloman (1990) and Gerrard (2000) give location factors for international locations from which this variation can be seen. It can be argued that as a result of globalization all international installation factors are trending closer to 1.0 (Gerrard, 2000). Location factors within a country are somewhat easier to predict and Bridgewater (1979) suggested a simple rule of thumb: add 10% for every 1000 miles from the nearest major industrial centre.

Table 6.7 gives example location factors relative to a USGC installation. These are based on data from Aspen Richardson's *International Construction Cost Factor Location Manual (2003)*. More recent versions of this manual can be found by searching for Richardson Engineering Services at www.aspentech.com. The values in Table 6.7 give costs on a local basis in U.S. dollars.

**Table 6.7 Location factors**

| Country | Region | Location factor |
|---|---|---|
| United Kingdom | | 1.02 |
| France | | 1.13 |
| Germany | | 1.11 |
| Italy | | 1.14 |
| Netherlands | | 1.19 |
| Russia | | 1.53 |
| India | | 1.02 |
| Middle East | | 1.07 |
| China | imported | 1.12 |
| | indigenous | 0.61 |
| Japan | | 1.26 |
| SE Asia | | 1.12 |
| Australia | | 1.21 |
| United States | Gulf coast | 1.00 |
| | East coast | 1.04 |
| | West Coast | 1.07 |
| | Midwest | 1.02 |
| Canada | Ontario | 1.00 |
| | Fort McMurray | 1.60 |
| Mexico | | 1.03 |
| Brazil | | 1.14 |

The location factors in Table 6.7 are based on 2003 data and can be updated by dividing by the ratio U.S. dollar/local currency in 2003 and multiplying by the ratio U.S. dollar/local currency in the year of interest. If a cost estimate for a future year is being made then currency variation will have to be forecasted. Currency exchange rates are published in the financial press and on foreign exchange web sites. Several web sites have excellent historic currency converter programs; see, for example, www.xe.com/ict/, www.x-rates.com/cgi-bin/hlookup.cgi and www.oanda.com/convert/fxhistory.

## EXAMPLE 6.4

The cost of constructing a 30,000 metric tons per year (30 kMTA) acrolein plant was estimated as $80 million ($80 MM) on a 2006 U.S. Gulf Coast basis. What would be the cost in Euros and in U.S. dollars on a 2006 Germany basis?

### Solution

From Table 6.7, the 2003 location factor for Germany was 1.11.

The exchange rate in 2003 averaged about €1 = US$1.15 and in 2006 it averaged about €1 = US$1.35.

The 2006 location factor for Germany is thus 1.11 × 1.35/1.15 = 1.30

The cost of building the acrolein plant in Germany in 2006 is US$80 MM × 1.30 = US$104 MM.

The cost of building the plant in Euros ($€_{2006}$) is US$104/1.35 = €77 million.

### 6.3.7 OFFSITE COSTS

Improvements to the site infrastructure are almost always needed when a new plant is added to a site or a major expansion is carried out. The cost of such improvements is known as the off-site or OSBL investment, as described in Section 6.2.1.

In the early stages of designing a new process, the off-site requirements are usually not precisely known and an allowance for off-site costs is made by assuming that they will be a ratio of the ISBL investment. A typical number is 20% to 50% of ISBL investment, depending on the process and site conditions. As the design details are established and the requirements for utilities such as steam, electricity and cooling water are determined, the site requirements can also be determined. Potential modifications to the infrastructure can then be designed to accommodate the new plant.

Many of the off-site items are designed as “packaged” plants or systems that are purchased from specialized suppliers. In some cases, the supplier may even offer an *over-the fence* contract, in which the supplier builds, owns and operates the off-site plant and contracts to supply the site with the desired utility stream or service. Over-the-fence contracts are widely used for industrial gases such as nitrogen, oxygen and hydrogen, and most plants also import electricity from the local utility company. Over-the-fence contracts for steam, cooling water and effluent treatment are less common, but are sometimes used in smaller plants or where several companies share a site.

The question of whether to build a self-contained infrastructure for a plant or contract for off-site services is an example of a *make or buy* problem. The over-the-fence price will usually be higher than the cost of producing the utility or service internally, since the supplier needs to make a profit and recover their capital investment. On the other hand, contracting for the service reduces the project capital investment and fixed costs, since the supplier must take on the costs of labour, maintenance and overheads. The make or buy decision is usually made by comparing annualized costs, as described in Section 6.7.6. Correlations for costs of utility plants and other off-sites are given in the sources listed in Section 6.3.4.

### 6.3.8 COMPUTER TOOLS FOR COST ESTIMATION

It is difficult for engineers outside the EPC sector to collect recent cost data from a large set of real projects and maintain accurate and up-to-date cost correlations. Instead, the most common method for making preliminary estimates in industry is to use commercial cost estimating software.

A wide variety of cost estimating programs is available. These include ACCE™ (Aspen Technology Inc.), Cleopatra Enterprise™ (Cost Engineering Consultancy), CostLink/CM (Building Systems Design, Inc.), Cost Track™ (OnTrack Engineering Ltd.), PRISM Project Estimator (ARES Corp.), Success Estimator (U.S. Cost), Visual Estimator (CPR Internation Inc.), WinEst® (Win Estimator®) and others that can be found by searching on the web or looking at the listings provided by AACE International at www.aacei.org. The discussion in this section will focus on Aspen Technology’s ACCE software, which is probably the most widely-used program and Cost Engineering Consultancy’s Cleopatra Enterprise, which has been developed using a data set that is more reflective of Northwest Europe and Middle East projects. Both of these programs have academic licenses available for university use and are also available in most chemical companies.

The ACCE and Cleopatra cost estimating tools are simple to use and give quick, defensible estimates without requiring a lot of design data. Design information can be uploaded from major flow-sheet simulation programs, or else entered manually. The programs allow the design to be updated as more information on design details becomes available, so that a more accurate estimate can be developed. Costs can be estimated for a whole plant or for one piece of equipment at a time. Both programs include a large number of equipment types and these can be designed in a broad range of materials, including U.S., U.K., German and Japanese standard alloys.

Both ACCE and Cleopatra use a combination of mathematical models and expert systems to develop cost estimates. Costs are based on the materials and labour required (following the practice used for detailed estimates) rather than installation factors. If design parameters are not specified by the user then they are calculated or set to default values by the program. The user should always review the design details carefully to make sure that the default values make sense for the application. If any values are not acceptable they can be manually adjusted and a more realistic estimate can be generated.

A detailed description of how to run ACCE or Cleopatra is beyond the scope of this book. Both programs have user manuals available from the licensor, or as .pdf files downloadable from the "help" button in the program, see for example AspenTech (2002a, 2002b). Some of the common issues that arise in using these programs are discussed below. These or similar problems are also faced when using other cost estimating software.

### *Mapping simulation data*

Instructions on loading data from a process simulation are given in the ACCE User's Guide (AspenTech, 2002a). When a simulator report file is loaded, ACCE generates a block-flow diagram with each unit operation of the simulation shown as a block. These blocks must then be "mapped" to ICARUS project components (pieces of equipment or bulk items).

Unless the user specifies otherwise, each simulator block is mapped to a default ICARUS project component. The mapping defaults need to be understood properly, as large errors can be introduced if unit operations are mapped incorrectly. The default mapping specifications are given in section 3 of the user's guide (AspenTech, 2002a). Some mappings that commonly cause problems include:

1. Reactors: plug-flow reactor models (PLUG in HYSYS and ProII, RPLUG in AspenPlus) are mapped to a packed tower, which is fine for fixed bed catalytic reactors, but not for other types of plug-flow reactor. All other reactor models (Gibbs, stoichiometric, equilibrium and yield) are mapped to agitated tank reactors. Reactors that are not suitable for these mappings can be mapped to other ICARUS project components or set up as user models (see below).
2. Heaters, coolers and heat exchangers: the default mapping for all heat transfer equipment is the floating head heat exchanger. ACCE contains several different heat exchanger types, including a generic TEMA heat exchanger that can be customized to the other types, as well as fired heater and air cooler components. It is often worthwhile to change the default mapping to the TEMA exchanger to allow the exchangers to be customized in ACCE.
3. Distillation columns: the simulator column models include not just the column itself, but also the reboiler, condenser, overhead receiver drum and reflux pump (but not bottoms pump). ACCE has ten possible configurations to which a column can be mapped. Alternatively, the column can be mapped to a packed or trayed tower and the ancillary items can be created as separate ICARUS project components.

4. Dummy items: process simulations often contain models of items that are not actual plant equipment (see Chapter 4). For example, heat exchangers are sometimes modelled as a series of heaters and coolers linked by a calculator block as a means of checking for internal pinch points or allowing for heat losses to ambient. When the simulation is mapped into ACCE, dummy items should be excluded from the mapping process. In the above example, only the heaters should be mapped, so as to avoid double counting the heat transfer area.

The default mapping can be edited by right-clicking on "Project Component Map Specifications" in the Project Basis/Process Design folder. A simulator model can be excluded from the mapping by selecting the item and then selecting "delete all mappings". New mappings can be specified by selecting a simulator item and adding a new mapping.

To map loaded simulator data, click the map button on the toolbar (which maps all items) or right-click on an area or plant item in the process view window (which allows items to be mapped individually). If individual items are selected then the user is given an option to use simulator data to override the default mapping in the Component Map Specs file. This is useful for heat exchangers and other equipment where the simulator allows the equipment type to be specified.

The procedure for mapping equipment in Cleopatra is somewhat simpler and is illustrated in Example 6.5 below.

### Design factors in ACCE

All good designs include an appropriate degree of over-design to allow for uncertainties in the design data and method (see Chapter 1). For some equipment the design factor or margin is specified by design codes and standards, for example, in the design of pressure vessels, as described in Chapter 13. In other cases, the design engineer must specify the degree of over-design or margin based on experience, judgement or company policy.

The equipment sizes calculated by a process simulator will be at the design flow rate unless a higher throughput was specified by the user, and hence include no design margin. The ACCE software adds an "equipment design allowance" to the equipment cost to allow for the design factor that will be introduced when the equipment is designed in detail. The equipment design allowance is based on the process description as follows:

| | |
|---|---|
| New and unproven process | 15% |
| New process | 10% |
| Redesigned process | 7% |
| Licensed process | 5% |
| Proven process | 3% |

The process description is entered by right-clicking on "General Specs" in the Project Basis/Basis for Capital Costs folder.

The equipment design allowance is only applied to system-developed costs. If different design margins are needed for different equipment types then the default should be set to "proven process" and the equipment can then be over-sized appropriately. Design margins can also be added to components using the ACCE custom model tool. Care should be taken to avoid adding more design margin than is necessary.

### Pressure vessels

When costing pressure vessels such as reactors and distillation columns, care must be taken to ensure that the wall thickness is adequate. The default method in both ACCE and Cleopatra calculates the wall thickness required based on the ASME Boiler and Pressure Vessel Code Section VIII Division 1 method for the case where the wall thickness is governed by containment of internal pressure (see Chapter 13 for details of this method). The programs can also allow for wind and seismic loads and design for under-pressure (vacuum). If other loads govern the design then the programs can significantly underestimate the vessel cost. This is particularly important for vessels that operate at pressures below 5 bara, where the required wall thickness is likely to be influenced by dead weight loads and bending moments from the vessel supports, and for tall vessels such as distillation columns and large packed-bed reactors. Similarly, if the vessel is designed under a different section of the Boiler and Pressure Vessel Code, which is usually the case for vessels operated at high pressures, then the programs can overestimate the vessel cost. It is important to always remember to enter the design pressure and temperature of the vessel, not the operating pressure and temperature.

The best approach to costing pressure vessels using commercial costing software is to enter all of the dimensions after completing the mechanical design of the vessel using the methods given in Chapter 13, or using suitable pressure vessel design software.

### Non-standard components in ACCE

Although ACCE contains over 250 equipment types, many processes require equipment that is not on the list of available project components. Also, in some cases the user will want to specify a certain make or model of equipment that may only be available in discrete sizes (for example, gas turbine engines or large pumps and compressors). In these situations, the non-standard equipment can be included by setting up an Equipment Model Library (EML). Many companies maintain standard EMLs listing equipment that they often specify.

A new EML can be created by selecting the “Libraries” tab in the palette and opening the folder Cost Libraries/Equipment Model Library. Right-clicking on either of the sub-folders then allows the user to create a new EML in the appropriate set of units. Once an EML has been created, equipment items can be added to it. When a new item is added, a dialog box opens in which the user has to specify the sizing or costing method (linear, log-log, semi-log or discrete) and primary sizing parameters. Two costs and sizes must also be entered to establish the cost correlation.

Equipment model libraries are useful for completing an IPE model of a process that contains non-standard items. Care must be taken to update the EML costs so that they remain current.

## EXAMPLE 6.5

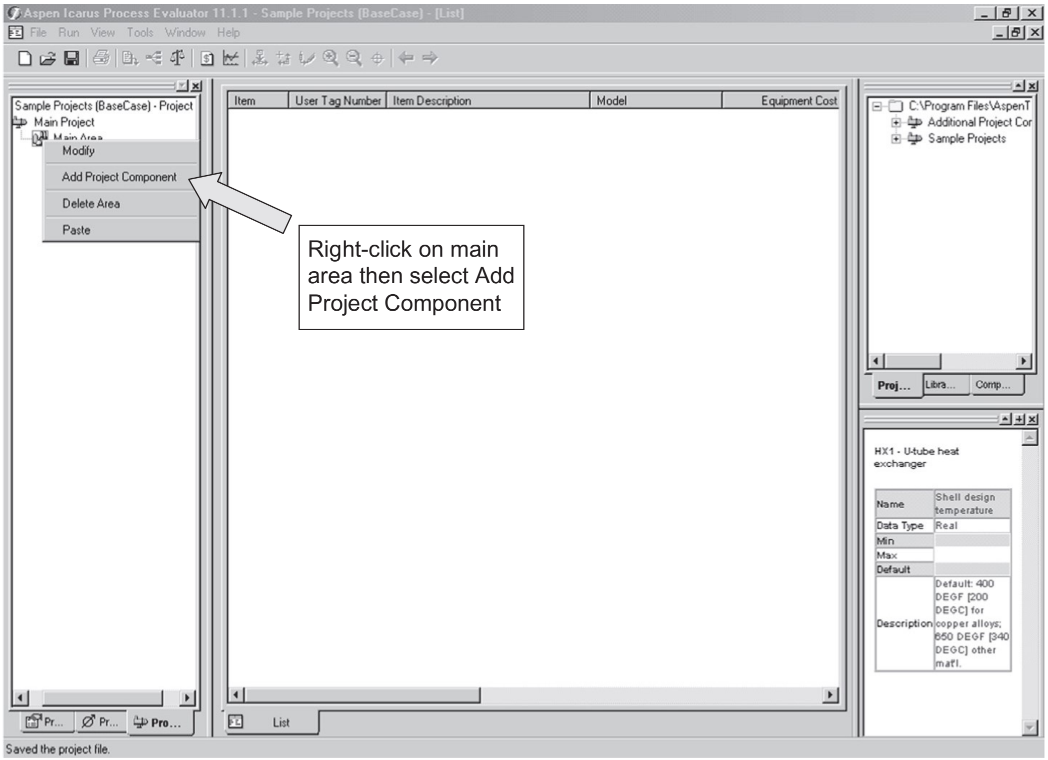
Estimate the cost of a waste heat boiler designed to produce 4,000 lb/h of steam. The exchanger area has been estimated as 1300 $ft^2$.

#### Solution in ACCE™

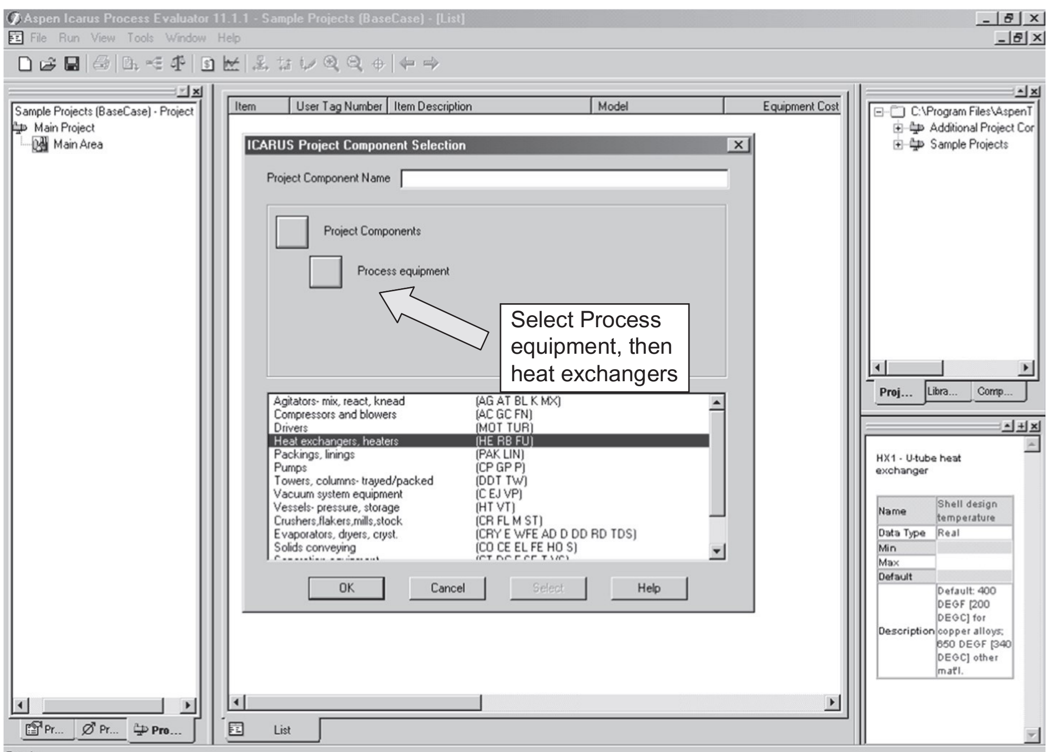
Starting from the ACCE project explorer window (on the far left of the screen), right-click on the Main Area and select Add Project Component, Figure 6.3*a*.

Select Process Equipment, then Heat Exchangers, Figure 6.3*b*. Select Waste Heat Boiler and enter a name, Figure 6.3*c*.

Enter the size parameters and then click the Evaluate button, Figure 6.3*d*. This runs the evaluator program and gives the results screen shown in Figure 6.3*e*. The purchased equipment cost is $145,900 on a Jan 2006 USGC basis. The installed cost is $196,225. Note that the installed cost is calculated directly by estimating bulk materials and labour rather than using an installation factor.




(a)

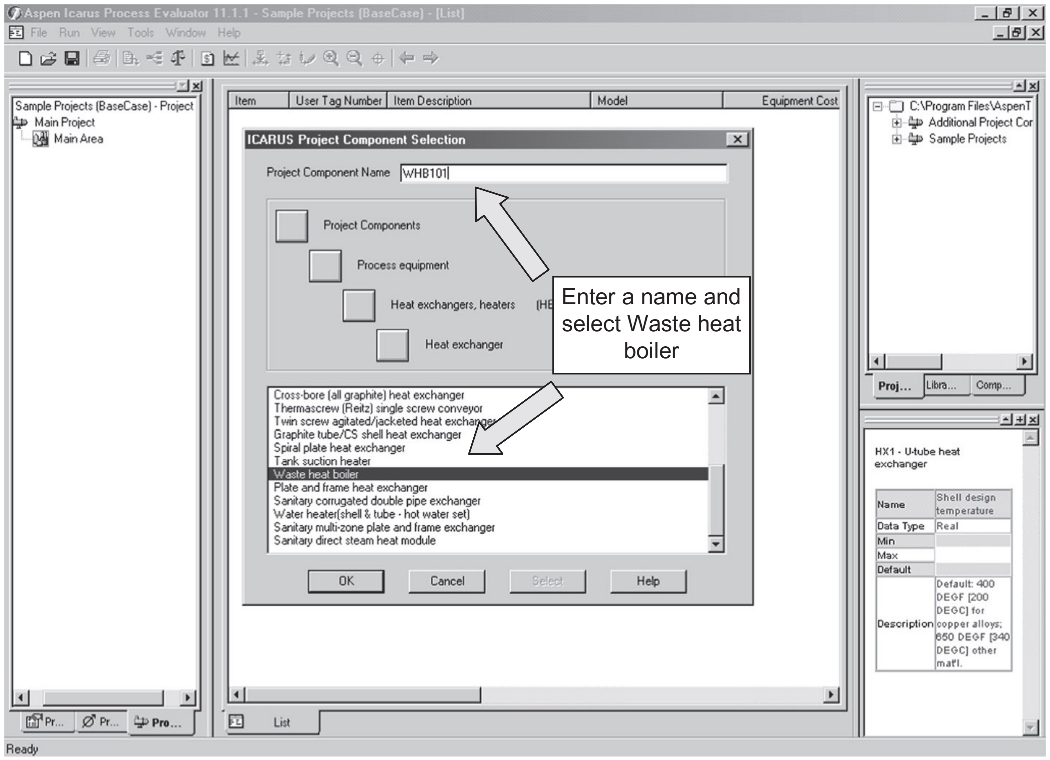



(b)

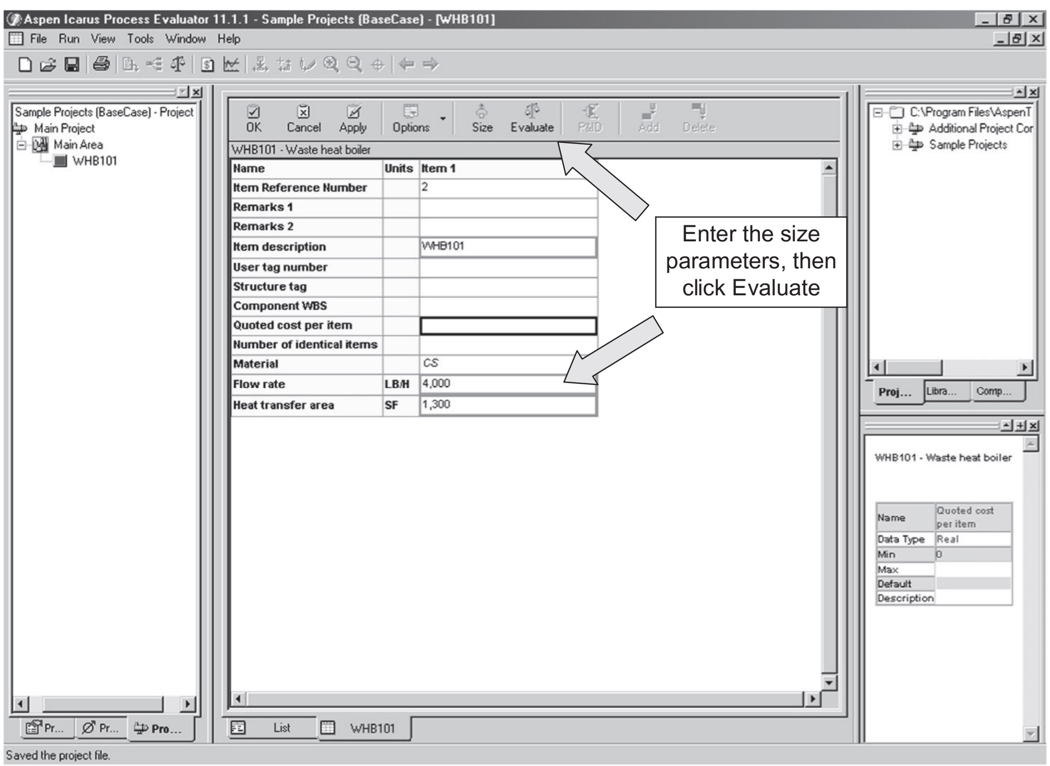
**FIGURE 6.3 (A, B)**

(a, b, c, d, e) ACCE example. (f, g, h, i) Cleopatra Enterprise example.

*Continued*

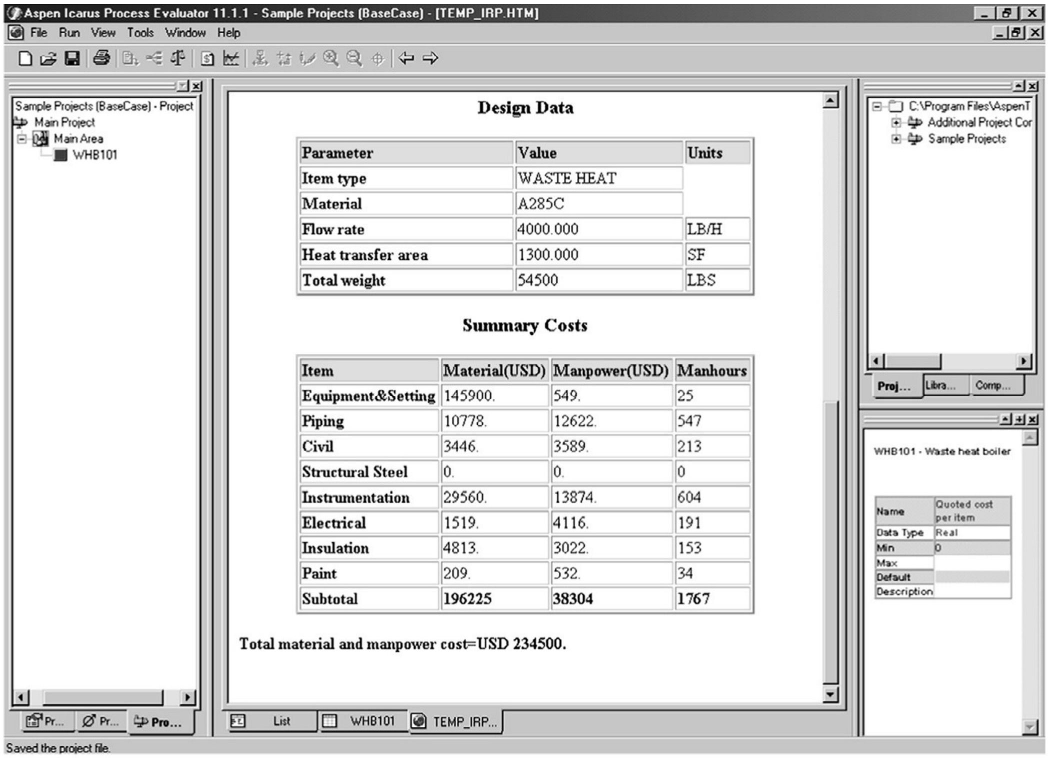



(c)




(d)

**FIGURE 6.3 (C,D)—cont'd**




| Parameter | Value | Units |
|---|---|---|
| Item type | WASTE HEAT | |
| Material | A285C | |
| Flow rate | 4000.000 | LB/H |
| Heat transfer area | 1300.000 | SF |
| Total weight | 54500 | LBS |

| Item | Material(USD) | Manpower(USD) | Manhours |
|---|---|---|---|
| Equipment&Setting | 145900. | 549. | 25 |
| Piping | 10778. | 12622. | 547 |
| Civil | 3446. | 3589. | 213 |
| Structural Steel | 0. | 0. | 0 |
| Instrumentation | 29560. | 13874. | 604 |
| Electrical | 1519. | 4116. | 191 |
| Insulation | 4813. | 3022. | 153 |
| Paint | 209. | 532. | 34 |
| Subtotal | 196225 | 38304 | 1767 |

(e)

**FIGURE 6.3 (E)—cont'd**

*Continued*

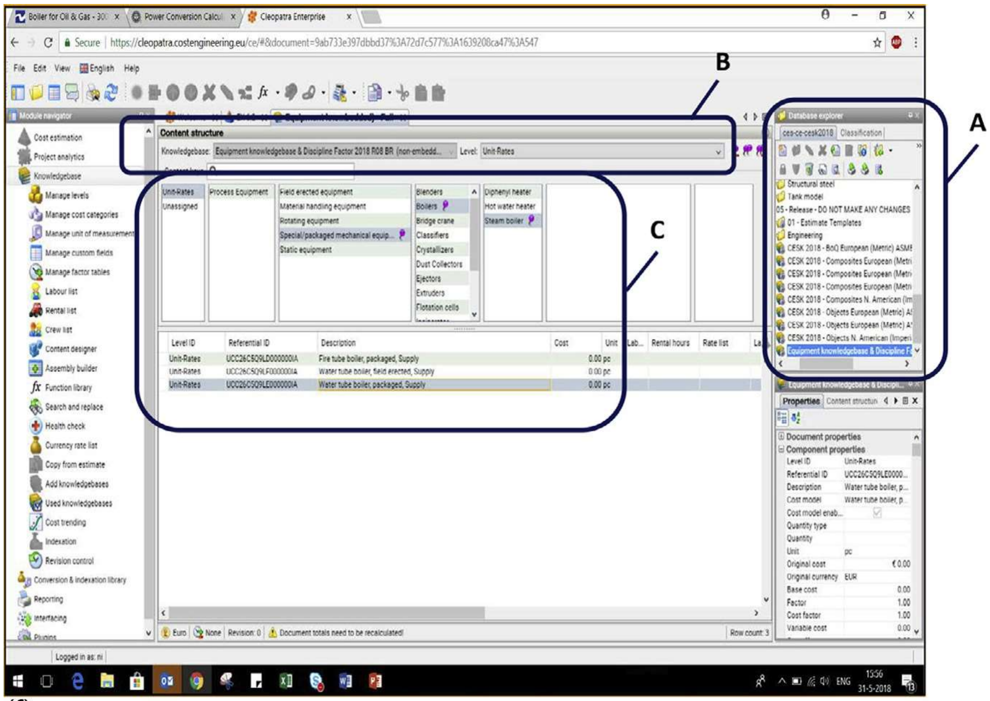
### Solution in Cleopatra Enterprise™

Starting from the Database Explorer (top right menu), create a new document for the estimate, Figure 6.3*f*, label A. Select the Estimating tab and then select the Equipment Knowledgebase tab and in the Level tab select "Unit-rates", Figure 6.3*f*, label B. Then work through the drop down menus to select Process Equipment / Special packaged mechanical equipment / Boilers / Steam boiler / Water tube packaged boiler, Figure 6.3*f*, label C.

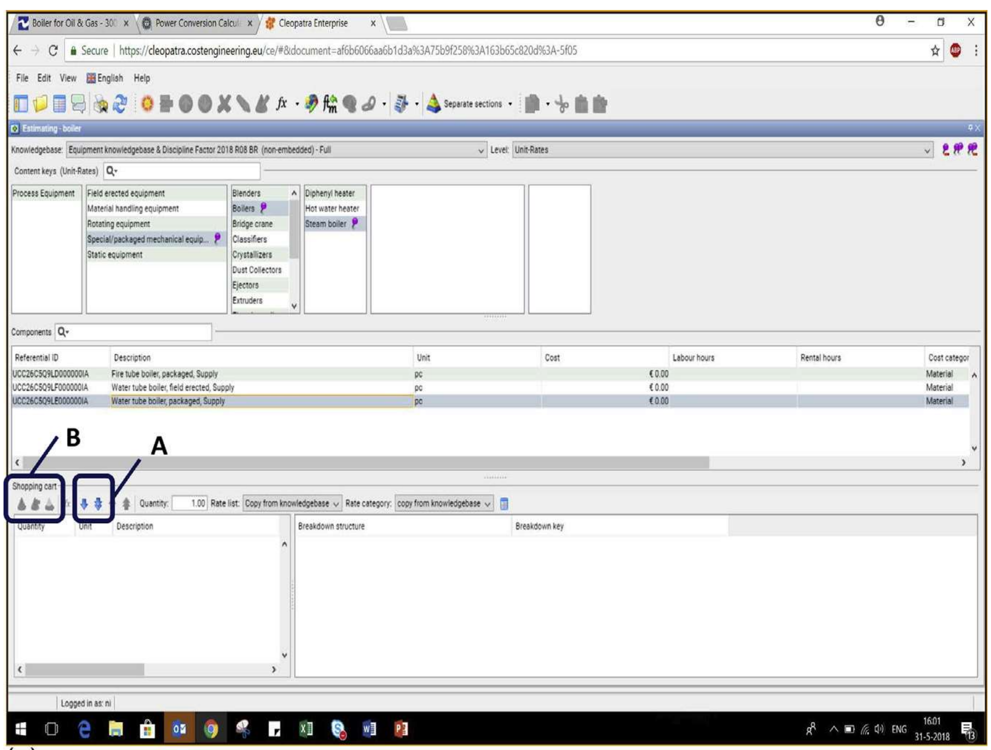
Clicking on the waste heat boiler then opens the menu for that item, Figure 6.3*g*, and allows the user to add it to the shopping cart (label A) and open the data entry window by clicking the pyramid plus icon (label B). The equipment data can then be entered, Figure 6.3*h*. the flowrate of 4,000 lb/h corresponds to a duty of roughly 1220 kW, and we can select 40 bar as operating pressure (a reasonable value for high-pressure steam). Cleopatra Enterprise then returns an equipment cost of $119,000 on a January 2018 US basis, and we can add this into an overall estimate by clicking the pyramid button at bottom right to give the results page shown in Figure 6.3*i*.

The cost generated by Cleopatra Enterprise is a bare-module cost for the equipment. We would need to enter more details about the plant layout and associated instrumentation and piping to generate an installed cost (or use a suitable Hand factor).

Note that the two programs do not give identical answers. This is a common occurrence when using costing software, as the different programs are based on different datasets. An experienced cost engineer will benchmark the results from the software against recent cost data for equipment they have purchased and tune the costing models to more accurately fit their experience of local costs. Tuning of the cost models is beyond the scope of this book, but is typically covered in the software user manuals.

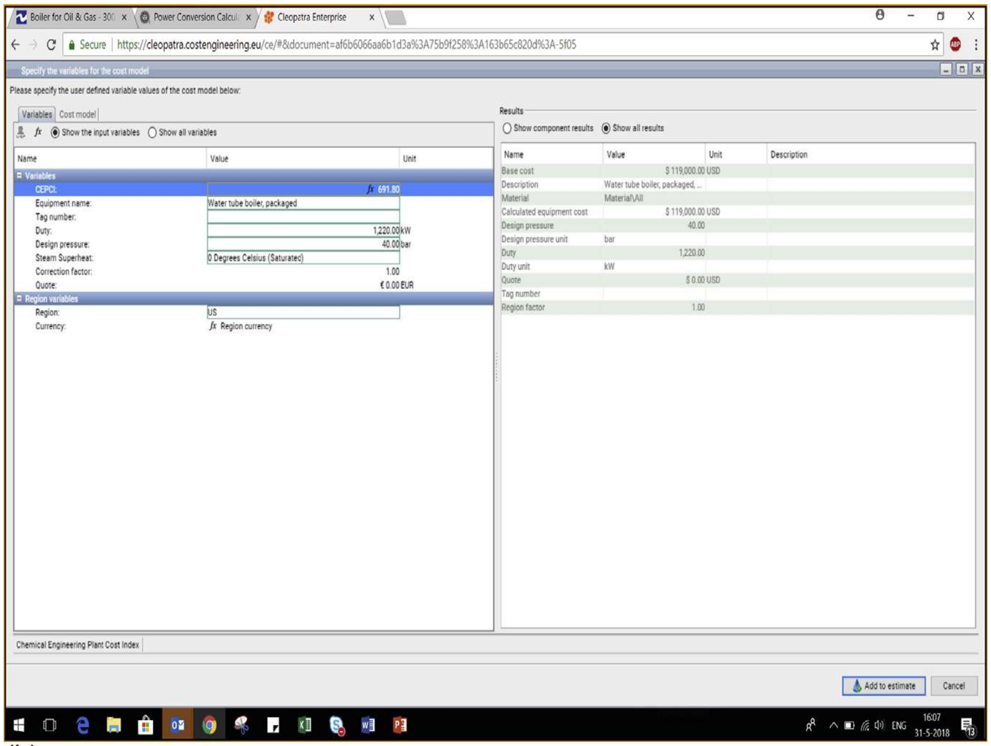



(f)

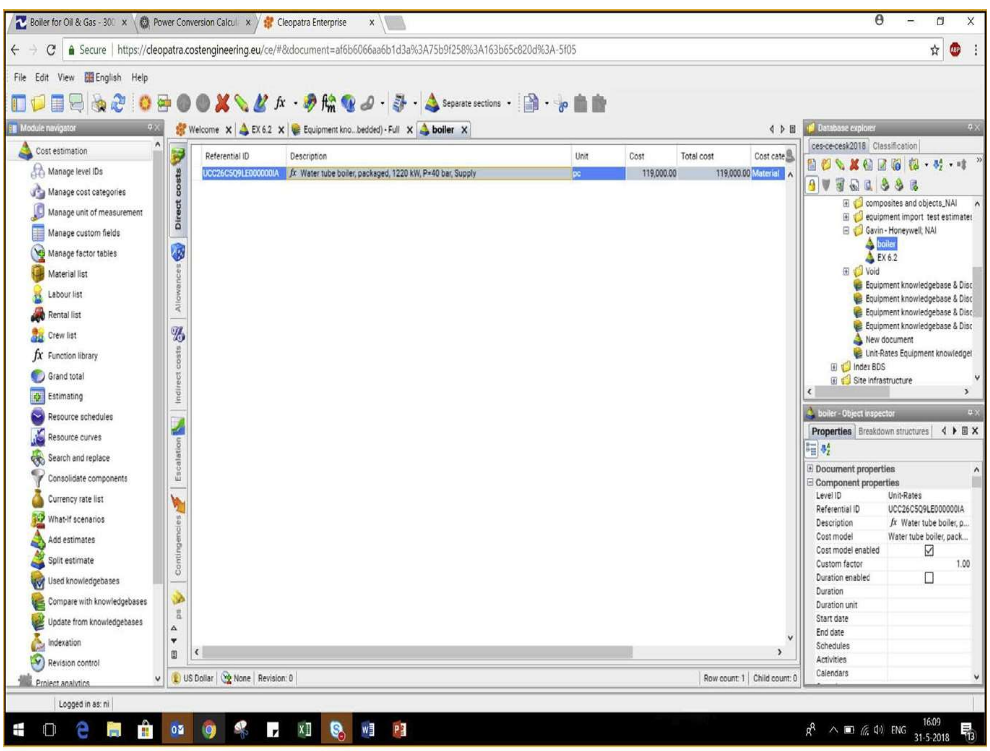



(g)

**FIGURE 6.3 (F, G)—cont'd**




(h)




(i)

**FIGURE 6.3 (H, I)—cont'd**

### 6.3.9 VALIDITY OF COST ESTIMATES

It should always be remembered that cost estimates are only estimates and are subject to error. An estimate should always indicate the margin of error. The error in a cost estimate is primarily determined by the degree of design detail that is available, and even a skilled estimator cannot estimate an accurate cost for a sketchy design.

When more design information has been developed a professional cost engineer will be able to develop a more accurate estimate. The process design engineer should compare this estimate with the preliminary estimate to gain a better understanding of where the preliminary estimate could have been improved (either through capturing missing plant items or using better costing methods). This will help the design engineer to produce better preliminary estimates in future.

Additional resources for cost estimating are available from the various cost estimating associations: the U.K. Association of Cost Engineers (www.acoste.org.uk); the Association for the Advancement of Cost Engineering International (www.aacei.org); the Project Management Institute (www.pmi.org); and the International Cost Engineering Council (www.icoste.org). The ICEC web site has links to cost engineering societies in 46 countries.

## 6.4 ESTIMATING PRODUCTION COSTS AND REVENUES

The revenues and variable costs of production are obtained by multiplying the product, feed or utility flow rates from the flow sheet by the appropriate prices. The difficult step is usually finding good price data.

### 6.4.1 SOURCES OF PRICE DATA

This section describes the most widely used sources of price data. Some pricing terminology is given in Table 6.8.

**Table 6.8 Pricing Terminology**

| Abbreviation | Meaning |
|---|---|
| c.i.f. | Cost, insurance and freight |
| dlvd. | Delivered |
| f.o.b. | Free on board |
| frt. alld. | Freight allowed |
| dms. | Drums |
| bgs. | Bags |
| refy. | Refinery gate |
| syn. | Synthetic |
| t.t. | Tank truck |
| t.c. | Tank car (rail) |
| t.l. | Truck load |
| imp. | Imported |

### *Internal company forecasts*

In many large companies the marketing or planning department develops official forecasts of prices for use in internal studies. These forecasts sometimes include multiple price scenarios, and projects must be evaluated under every scenario. Company forecasts are occasionally made available to the public. See for example Shell (2013) or Shell (2018), which can be downloaded from www.Shell.com. When an officially-approved price set exists, the design engineer should use it. The main concern is then ensuring that prices for feeds, products or consumables that are not part of the standard forecast are put on a consistent basis.

### *Trade journals*

Several journals publish chemicals and fuel prices on a weekly basis:

*ICIS Chemical Business Americas* – formerly known as *Chemical Marketing Reporter* (ICIS Publications) used to list prices for 757 chemicals with multiple locations and product grades for some. This list was reduced to only 85 compounds in 2006, with most of the remaining set being natural extracts. Data for 80 chemicals, 44 fuels and 11 base oils is now provided on-line through the subscription service www.icispricing.com. At the time of writing this service was very expensive compared to some of the alternatives listed below. ICIS also publishes *ICIS Chemical Business Europe* (formerly *European Chemical News*) and *ICIS Chemical Business Asia*, which provide regional price data for a smaller set of compounds.

The *Oil and Gas Journal* (Pennwell) publishes prices for several crude oils and a range of petroleum products on U.S., N.W. Europe and S.E. Asia bases, as well as natural gas prices for the U.S.A.

*Chemical Week* (Access Intelligence) gives spot and contract prices for 22 commodity chemicals in U.S. and N.W. Europe markets.

### *Consultants*

There are many companies that can be hired as consultants to provide economic and marketing information, or that allow access to such information on a subscription basis. The information provided generally includes market surveys and technical and economic analyses of competing technologies as well as price data and forecasts. There is not room here to list all of these companies, but some of the most widely used are:

- *Purvin and Gertz*: Provides quarterly forecasts of oil, gas and fuels prices that are widely used in the oil industry. They have a 10-year archive of historic data and forecast prices of most fuel products as well as crude oils on U.S., N.W. Europe, Middle East and Asia bases.
- *Cambridge Energy Research Associates*: Publishes forecasts of crude oil prices based on macroeconomics and industry trends (drilling rates, etc.).
- *Chemical Market Associates Inc*. (CMAI): Maintains a large archive of historic data and future price forecasts for 70 commodity chemicals, including multiple grades, U.S., N.W. Europe, Middle East, N.E. and S.E. Asia. Spot and contract prices are given for some compounds and in some cases margins are also estimated by formula.
- *SRI*: The *Chemical Economics Handbook* series of reports published by SRI provides overviews of the markets for 288 compounds. These reports are not updated as frequently as the others, but are useful for less commoditized compounds.

#### *On-line brokers and suppliers*

Much price data is available on-line from suppliers' web sites that can be found through directory sites such as www.purchasing.com and www.business.com/directory/chemicals.

Some caution is needed when using price data from the web. The prices quoted are generally for spot sale of small quantity orders, and are thus much higher than the market rates for large order sizes under long-term contract. The prices listed on-line are also often for higher quality material such as analytical, laboratory or USP pharmaceutical grades, which have much higher prices than bulk grades.

#### *Reference books*

Prices for some of the more common commodity chemicals are sometimes given in process economics textbooks. These prices are usually single data points rather than forecasts. They are only suitable for undergraduate design projects.

### 6.4.2 FORECASTING PRICES

In most cases, it will take between one and three years for a project to go through the phases of design, procurement and construction before the plant can begin operation. The plant will then operate for the project life of ten to twenty years. The design engineer thus needs to carry out the economic analysis using prices forecasted over the next twenty or so years rather than the current price when the design is carried out.

For some compounds the only variation in price over time is minor adjustments to allow for inflation. This is the case for some specialty compounds that have relatively high prices and are not subject to competitive pressure (which tends to drive prices down). Prices can also be stable if they are controlled by governments, but this is increasingly rare. In most cases, however, prices are determined largely by feedstock prices, which are ultimately determined by fluctuations in the prices of commodity fuels and chemicals. The prices of these commodities are set by markets in response to variations in supply and demand, and vary widely over time.

Most price forecasts are based on an analysis of historic price data. Several methods are used, as illustrated in Figure 6.4. The simplest method is to use the current price, Figure 6.4*a*, but this is unsatisfactory for most commodities. Linear regression of past prices is a good method for capturing long-term trends (>10 years), but can give very different results depending on the start date chosen, as shown in Figure 6.4*b*. This method can be very misleading if the data set is too small.

Many commodity prices exhibit cyclic behaviour due to the investment cycle, so in some cases non-linear models can be used, Figure 6.4*c*. Unfortunately, both the amplitude and the frequency of the price peaks usually vary somewhat erratically, making it difficult to fit the cyclic price behaviour with simple wave models or even advanced Fourier transform methods.

A fourth approach, illustrated in Figure 6.4*d* is to recognize that feed and product prices are usually closely linked, since increases in feed costs are passed on to customers whenever possible via increases in product price. Although feed and product prices may both be variable, the gross margin is therefore subject to much less variation and can be forecasted more reliably. Forecasting of margins is the method used widely in the fuels and petrochemicals industry as it is much easier to predict the variation in margins than the underlying variation in the prices of crude oil and natural gas. The drawbacks of this method are that it does not work so well when there are multiple routes to the same product, and it involves making assumptions about yields that may not hold true throughout the forecast period. In cases where the gross margin is high, it can be more difficult for the manufacturer to pass on the full impact of feedstock price increases in the form of increased

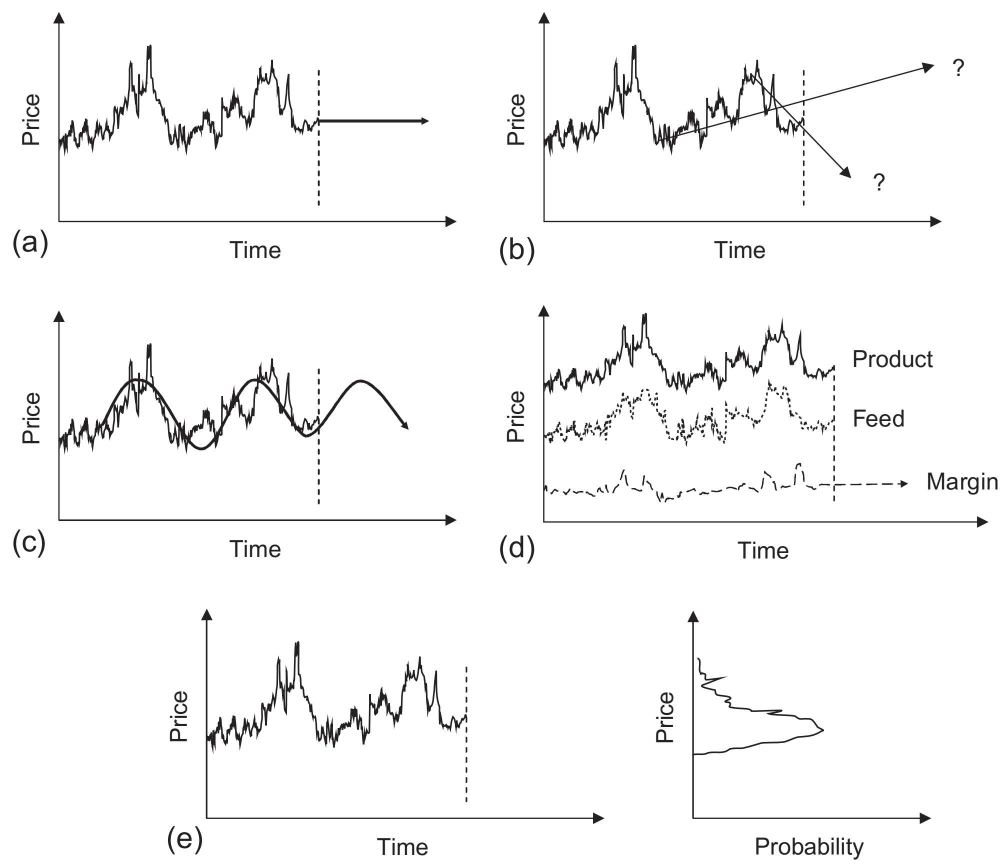



**FIGURE 6.4**

(a, b, c, d, e) Forecasting commodity prices.

product prices. In such cases, when feed prices rise rapidly there is a drop in margins while producers wait for the market to absorb the impact of higher prices.

Another method is to model the statistical distribution of the price (or margin) as illustrated in Figure 6.4*e*. At its simplest, this method involves taking the average price, adjusted for inflation, over a recent period. This method can miss long-term trends in the data and few prices follow any of the more commonly used distributions. It is useful, however, in combination with sensitivity analysis methods such as Monte Carlo Simulation (see Section 6.8).

Figure 6.5 shows North American prices from CMAI data for polyethylene terephthalate resin (PET), which is made from terephthalic acid (TPA), which in turn is made from paraxylene (PX). Several things are apparent from Figure 6.5:

1. The spot prices of PX and TPA show more volatility than the contract prices, as would be expected.
2. All the prices follow the same broad trends, with a major peak in 1995 and long recovery leading to a second peak in 2006.
3. The sharp peak in PX spot price in 1995 was not passed on to the other prices.

Figure 6.6 shows the simple margins TPA-PX and PET-PX over the same time period, all based on contract prices. The degree of variation in margins is clearly less than the variation in the base prices. There also appears to be a long-term decline in TPA margins relative to PX.

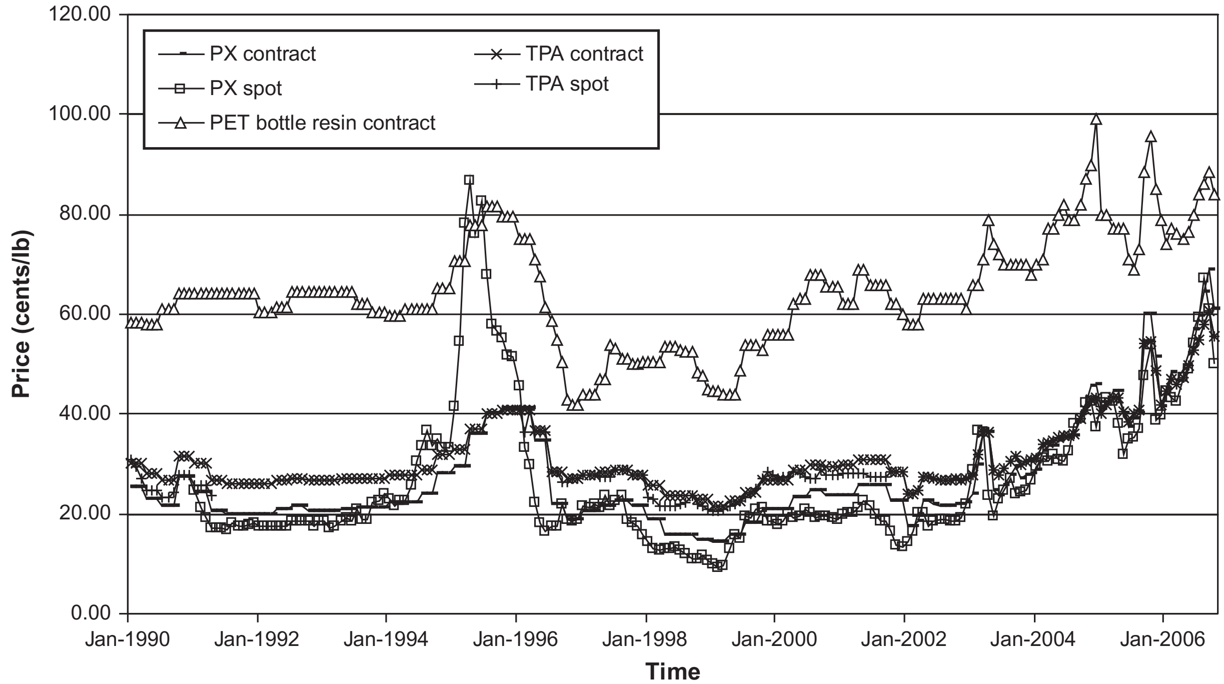



**FIGURE 6.5**

North American prices for the PET value chain.

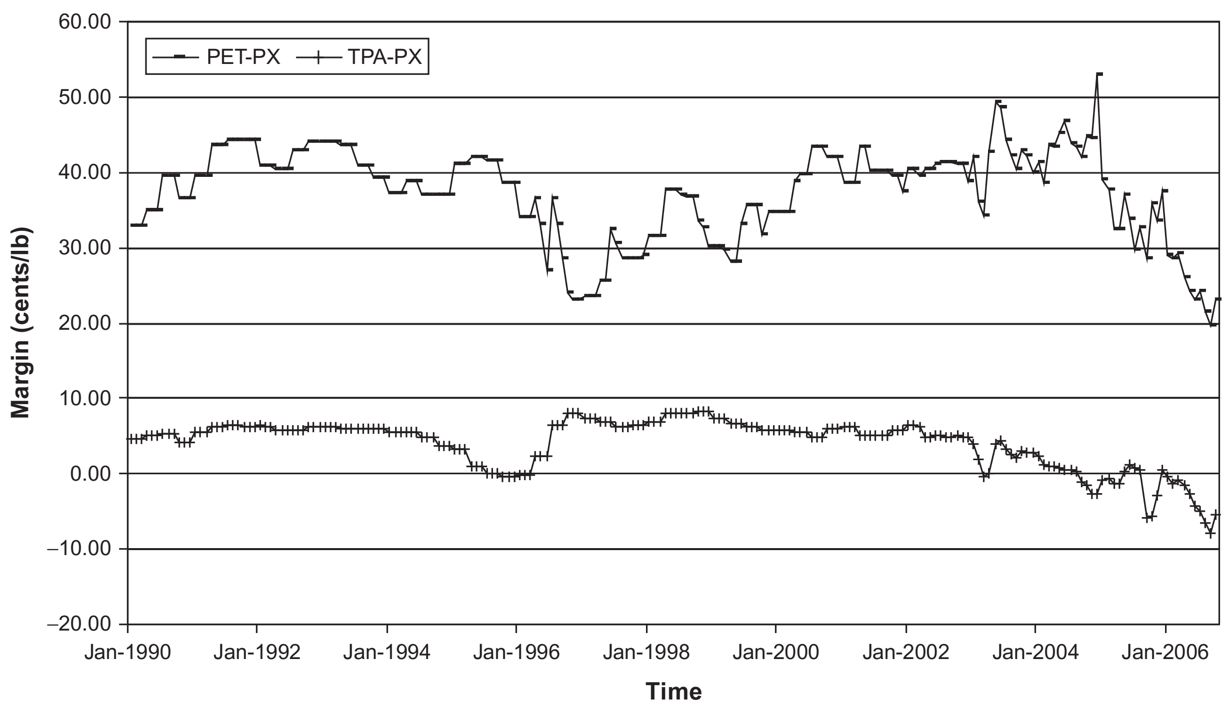



**FIGURE 6.6**

Simple margins for the PET value chain.

A similar examination of feed and product prices along the value chain of a given chemical can usually provide valuable insights into the best method of forecasting. No method is perfect, and anyone capable of accurately predicting commodity prices would be well advised to pursue a more lucrative career than chemical engineering. For process design purposes it is usually sufficient to show that the prices used for optimization and economic analysis are realistic and consistent with consensus views of the market.

### 6.4.3 TRANSFER PRICING

If the raw material for plant B is the product of plant A on the same site and owned by the same company, then the price that plant B pays to plant A is known as a "transfer price". Whenever realistic, transfer prices should be set by open market prices. This reflects the reality that plant A could sell its product on the open market or plant B could similarly buy its feed. Some cases when transfer prices do not match market prices include:

1. When plant A produces material that is suitable for internal consumption but does not meet specifications for traded product. In this case, the transfer price to plant B should be discounted to allow for the added costs incurred in plant B from handling the less pure feed.
2. When plant A is underutilized or cannot sell its product and has recovered all of its initial capital investment, then the transfer price to plant B can be set at the cash cost of production of plant A (see Section 6.2.5). This encourages maximum use of the existing asset of plant A and thereby reduces the fixed costs per kilogram of product from plant A and makes it more competitive.
3. When the pricing of product from the upstream plant is set to drive capacity utilization or conservation, for example, by using a sliding price scale based on the amount of material used.

When transfer pricing is used it is important to keep in mind which processes actually bring in money from customers and which do not. If unrealistic transfer prices are used, uneconomic projects may seem attractive and poor investment decisions may be made.

### 6.4.4 UTILITY COSTS

The utility consumption of a process cannot be estimated accurately without completing the material and energy balances and carrying out a pinch analysis, as described in Chapter 3. The pinch analysis gives targets for the minimum requirements of hot and cold utility. More detailed optimization then translates these targets into expected demands for fired heat, steam, electricity, cooling water and refrigeration. In addition to the utilities required for heating and cooling, the process may also need process water and air for applications such as washing, stripping and instrument air supply. A good overview of methods for design and optimization of utility systems is given by Smith (2016).

The electricity demand of the process is mainly determined by the work required for pumping, compression, air coolers and solids-handling operations, but also includes the power needed for instruments, lights and other small users. Some plants generate their own electricity using a gas-turbine cogeneration plant with a heat recovery steam generator (waste heat boiler) to raise steam, Figure 6.7. The cogeneration plant can be sized to meet or exceed the plant electricity requirement, depending on whether the export of electricity is an attractive use of capital.

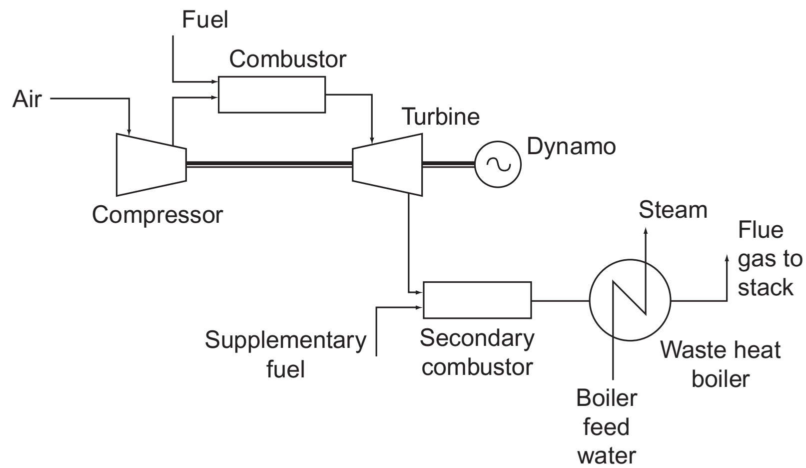



**FIGURE 6.7**

Gas-turbine based cogeneration plant.

Most plants are located on sites where the utilities are provided by the site infrastructure. The price charged for a utility is mainly determined by the operating cost of generating and transmitting the utility stream. Some companies also include a capital recovery charge in the utility cost, but if this is done then the offsite (OSBL) capital cost must be reduced to avoid double counting and biasing the project capital-energy trade-off, leading to poor use of capital.

Some smaller plants purchase utilities "over the fence" from a supplier such as a larger site or a utility company, in which case the utility prices are set by contract and are typically pegged to the price of natural gas or fuel oil.

### *Fired heat*

Fired heaters are used for process heating above the highest temperatures that can be reached using high pressure steam, typically about 250 °C (480 °F). Process streams may be heated directly in the furnace tubes, or indirectly using a hot oil circuit. The design of fired heaters is described in Chapter 12. The cost of fired heat can be calculated from the price of the fuel fired. Most fired process heaters use natural gas, as it is cleaner burning than fuel oil and therefore easier to fit $NO_x$ control systems and obtain permits. Natural gas also requires less maintenance of burners and fuel lines and natural gas burners can often co-fire process waste streams such as hydrogen, light hydrocarbons, or air saturated with hydrocarbons or solvents. In recent years, North American and European prices for natural gas have had very high mid-winter peaks. This has caused some plants to revert to using heating oil as fuel.

Natural gas and heating oil are traded as commodities and prices can be found at on-line trading sites or business news sites (e.g., http://markets.ft.com or www.cnn.money.com). Historic prices for forecasting can be found in the *Oil and Gas Journal* or from the U.S. Energy Information Agency (www.eia.doe.gov). The EIA also has an extensive database of historic international prices for natural gas, heating oil and electricity (www.eia.doe.gov/emeu/international).

The fuel consumed in a fired heater can be estimated from the fired heater duty divided by the furnace efficiency. The furnace efficiency will typically be about 0.85 if both the radiant and convective sections are used (see Chapter 12) and about 0.6 if the process heating is in the radiant section only.

### *Steam*

Steam is the most widely-used heat source on most chemical plants. Steam has a number of advantages as a hot utility:

- The heat of condensation of steam is high, giving a high heat output per pound of utility at constant temperature (compared to other utilities such as hot oil and flue gas that release sensible heat over a broad temperature range).
- The temperature at which heat is released can be precisely controlled by controlling the pressure of the steam. This enables tight temperature control, which is important in many processes.
- Condensing steam has very high heat transfer coefficients, leading to cheaper heat exchangers.
- Steam is non-toxic, non-flammable, visible if it leaks externally and inert to many (but not all) process fluids.

Most sites have a pipe network supplying steam at three or more pressure levels for different process uses. A typical steam system is illustrated in Figure 6.8. Boiler feed water at high pressure is preheated and fed to boilers where high pressure steam is raised and superheated above the dew point to allow for heat losses in the piping. Boiler feed water preheat can be accomplished using process waste heat or convective section heating in the boiler plant. High pressure (HP) steam is typically at about 40 bar, corresponding to a condensing temperature of 250 °C, but every site is different. Some of the HP steam is used for process heating at high temperatures. The remainder of the HP steam is expanded either through steam turbines known as *back-pressure turbines* or through let-down valves to form medium pressure (MP) steam. The pressure of the MP steam mains varies widely from site to site,

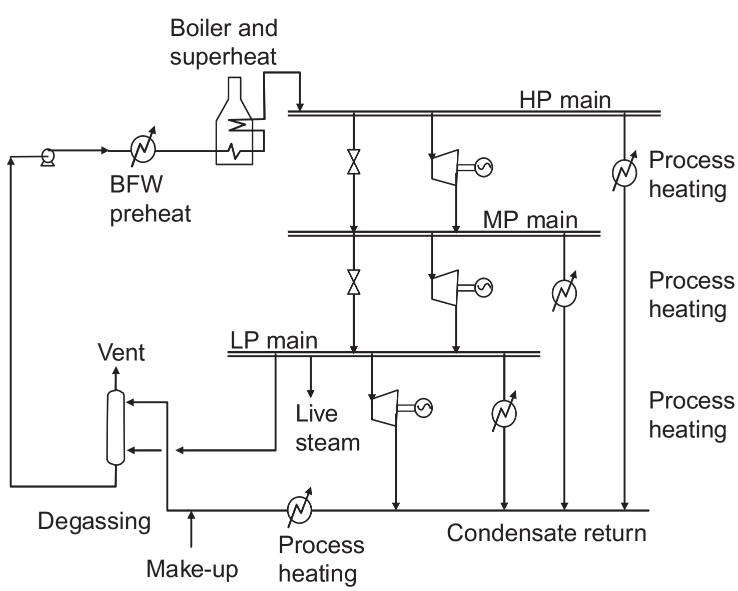



**FIGURE 6.8**

Steam system.

but is typically about 20 bar, corresponding to a condensing temperature of 212 °C. Medium pressure steam is used for intermediate temperature heating or expanded to form low pressure (LP) steam, typically at about 3 bar, condensing at 134 °C. Some of the LP steam may be used for process heating if there are low temperature heat requirements. Low pressure (or MP or HP) steam can also be expanded in condensing turbines to generate shaft work for process drives or electricity production. A small amount of LP steam is used to strip dissolved non-condensable gases such as air from the condensate and make-up water. Low pressure steam is also often used as "live steam" in the process, for example, as stripping vapour or for cleaning, purging or sterilizing equipment.

When steam is condensed without coming into contact with process fluids, then the hot condensate can be collected and returned to the boiler feed water system. Condensate can also sometimes be used as a low temperature heat source if the process requires low temperature heat.

The price of HP steam can be estimated from the cost of boiler feed water treatment, the price of fuel and the boiler efficiency:

$$P_{HPS} = P_F \times \frac{dH_b}{\eta_B} + P_{BFW} \tag{6.18}$$

where:

$P_{HPS}$ = price of high pressure steam (£/t)
$P_F$ = price of fuel (£/GJ)
$dH_b$ = heating rate (GJ/t steam)
$\eta_B$ = boiler efficiency
$P_{BFW}$ = price or cost of boiler feed water (£/t)

Package boilers typically have efficiencies similar to fired heaters, in the range 0.8 to 0.9.

The heating rate should include boiler feed water preheat, the latent heat of vaporization and the superheat specified.

The cost of boiler feed water includes allowances for water make-up, chemical treatment and degassing, and is typically about twice the cost of raw water (see below). If no information on the price of water is available, then 0.50 £/t (~0.50 \$/1000 lb) can be used as an initial estimate. If the steam is condensed and the condensate is returned to the boiler feed water (which will normally be the case), then the price of steam should include a credit for the condensate. The condensate credit will often be close enough to the boiler feed water cost that the two terms cancel each other out and can be neglected.

The prices of medium and low pressure steam are usually discounted from the high pressure steam price, to allow for the shaft work credit that can be gained by expanding the steam through a turbine, and also to encourage process heat recovery by raising steam at intermediate levels and using low-grade heat when possible. Several methods of discounting are used. The most rational of these is to calculate the shaft work generated by expanding the steam between levels and price this as equivalent to electricity (which could be generated by attaching the turbine to a dynamo or else would be needed to run a motor to replace the turbine if it is used as a driver). The value of the shaft work then sets the discount between steam at different levels. This is illustrated in the following example.

## EXAMPLE 6.6

A site has steam levels at 40 bar, 20 bar and 6 bar. The price of fuel is £4/GJ and electricity costs £0.05/kWh. If the boiler efficiency is 0.8 and the steam turbine efficiency is 0.85, suggest prices for HP, MP and LP steam.

### Solution

The first step is to look up the steam conditions, enthalpies and entropies in steam tables:

| Steam level | HP | MP | LP |
|---|---|---|---|
| Pressure (bar) | 40 | 20 | 6 |
| Saturation temperature (°C) | 250 | 212 | 159 |

The steam will be superheated above the saturation temperature to allow for heat losses in the pipe network. The following superheat temperatures were set to give an adequate margin above the saturation temperature for HP steam and also to give (roughly) the same specific entropy for each steam level. The actual superheat temperatures of MP and LP steam will be higher, due to the non-isentropic nature of the expansion.

| | | | |
|---|---|---|---|
| Superheat temperature (°C) | 400 | 300 | 160 |
| Specific entropy, $s_g$, (kJ/kg.K) | 6.769 | 6.768 | 6.761 |
| Specific enthalpy, $h_g$, (kJ/kg) | 3214 | 3025 | 2757 |

We can then calculate the difference in enthalpy between levels for isentropic expansion:

| | | |
|---|---|---|
| Isentropic delta enthalpy (kJ/kg) | 189 | 268 |

Multiplying by the turbine efficiency gives the non-isentropic enthalpy of expansion:

| | | |
|---|---|---|
| Actual delta enthalpy (kJ/kg) | 161 | 228 |

This can be converted to give the shaft work in kWh/t:

| | | |
|---|---|---|
| Shaft work (kWh/t) | 44.7 | 63.3 |

Multiplying by the price of electricity converts this into a shaft work credit:

| | | |
|---|---|---|
| Shaft work credit (£/t) | 2.24 | 3.17 |

The price of high pressure steam can be found from equation 6.18, assuming that the boiler feed water cost is cancelled out by a condensate credit and the heating rate is 2.2 GJ/t steam (allowing for some boiler feed water preheat). The other prices can then be estimated by subtracting the shaft work credits.

| | | | |
|---|---|---|---|
| Steam price (£/t) | 11.0 | 8.76 | 5.59 |

For quick estimates, this example can easily be coded into a spreadsheet and updated with the current prices of fuel and power. A sample steam costing spreadsheet is available in the on-line material at http://books.elsevier.com/companions.

### Cooling

The cost of process cooling usually depends strongly on the cost of power (electricity).

- Air coolers use electric power to run the fans. The power requirement is determined as part of the cooler design, as described in Chapter 12.
- Cooling water systems use power for pumping the cooling water through the system and for running fans (if installed) in the cooling towers. They also have costs for water make-up and chemical treatment. The power used in a typical recirculating cooling water system is usually between 1 and 2 kWh/1000 US gal (3.8 $m^3$) of circulating water. The costs of water make-up and chemical treatment usually add about $0.02/1000 gal circulated (£2.60 /thousand metric tons).
- Refrigeration systems use power to compress the refrigerant. The power can be estimated using the cooling duty and the refrigerator coefficient of performance (*COP*).

$$COP = \frac{\text{Refrigeration produced (Btu/hr or MW)}}{\text{Shaft work used (Btu/hr or MW)}} \tag{6.19}$$

The *COP* is a strong function of the temperature range over which the refrigeration cycle operates. For an ideal refrigeration cycle (a reverse Carnot cycle), the *COP* is:

$$COP = \frac{T_1}{(T_2 - T_1)} \tag{6.20}$$

where:

$T_1$ = evaporator absolute temperature (K)
$T_2$ = condenser absolute temperature (K)

The COP of real refrigeration cycles is always less than the Carnot efficiency. It is usually about 0.6 times the Carnot efficiency for a simple refrigeration cycle, but can be as high as 0.9 times the Carnot efficiency if complex cycles are used. Good overviews of refrigeration cycle design are given by Dincer (2017), Stoecker (1998) and Hundy *et al.* (2008).

### Electricity

Chemical plants consume large enough amounts of electricity that it is often economically attractive for them to install gas turbine engines or steam turbines and generate their own electric power. This "make or buy" scenario gives chemical producers strong leverage when negotiating electric power contracts and they are usually able to purchase electricity at or close to wholesale prices. Wholesale electricity prices vary internationally (see www.eia.doe.gov/emeu/international for details), but are typically in the range $0.05 to $0.12/kWh in most developed economies at the time of writing.

### Water

Raw water is brought in to make up for losses in the steam and cooling water systems and is also treated to generate demineralized and deionized water for process use. The price of water varies strongly by location, depending on fresh water availability. Water prices are often set by local government bodies and often include a charge for waste water rejection. This charge is usually applied on the basis of the water consumed by the plant, regardless of whether that water is actually rejected as a liquid (as opposed to being lost as vapour or incorporated into a product by reaction).

A very rough estimate of water costs can be made by assuming \$2 per 1000 gal (0.26 £/t). Demineralized water typically costs about double the price of raw water, but this obviously varies strongly with the mineral content of the water and the disposal cost of effluents from the demineralization system. Water demineralization is discussed in the sections on ion exchange and reverse osmosis in Chapter 10.

### Air and nitrogen

Air at 1 atmosphere pressure is freely available in most chemical plants. Compressed air can be priced based on the power needed for compression (see Chapter 3). Drying the air, for example for instrument air, typically adds about \$0.005 per standard $m^3$ (\$0.14/1000 scf). Nitrogen and oxygen are usually purchased from one of the industrial gas companies via pipeline or a small dedicated over-the-fence plant. The price varies depending on local power costs, but is typically in the range \$20 to \$70 per metric ton (\$0.01 to \$0.03 per lb) for large facilities.

## EXAMPLE 6.7

Estimate the annual cost of providing refrigeration to a condenser with duty 1.2 MW operating at −5 °C. The refrigeration cycle rejects heat to cooling water that is available at 40 °C, and has an efficiency of 80% of the Carnot cycle efficiency. The plant operates for 8000 hours per year and electricity costs €0.06/kWh.

### Solution

The refrigeration cycle needs to operate with an evaporator temperature below −5 °C, say at −10°C or 263 K. The condenser must operate above 40 °C, say at 45 °C (318 K).

For this temperature range the Carnot cycle efficiency is:

$$COP = \frac{T_1}{(T_2 - T_1)} = \frac{263}{318 - 263} = 4.78 \quad (6.20)$$

If the cycle is 80% efficient then the actual coefficient of performance = 4.78 × 0.8 = 3.83

The shaft work needed to supply 1.2 MW of cooling is given by:

$$\text{Shaft work required} = \frac{\text{Cooling duty}}{COP} = \frac{1.2}{3.83} = 0.313\,\text{MW}$$

The annual cost is then = 313 kW × 8000 h/y × 0.06 €/kWh = 150,000 €/y

## 6.4.5 CONSUMABLES COSTS

Consumables include materials such as acids, bases, sorbents, solvents and catalysts that are used in the process. Over time these become depleted or degraded and require replacement. In some cases a continuous purge and make-up is used (for example, for acids and bases), while in other cases an entire batch is periodically replaced (for example, for sorbents and catalysts).

The prices of acids, bases and solvents can be found from the same sources used for raw materials prices. Whenever possible, the cheapest base (NaOH) or acid ($H_2SO_4$) would be used in the process, but for neutralizing spent sulphuric acid, lime (CaO) or ammonia ($NH_3$) are often used, as these bases react with sulphuric acid to form insoluble sulphates that can be recovered and sold as by-products. Acids and bases are also consumed in ion exchange units that are used to treat process feed water and boiler feed water; see Chapter 10. The cost of process acid or base must always include the costs of neutralizing the spent stream.

The price of adsorbents and catalysts varies very widely depending on the nature of the material. The cheapest catalysts and adsorbents cost less than \$2/kg, while more expensive catalysts containing noble metals such as platinum and palladium have costs that are mainly determined by the amount of precious metal on the catalyst. In some cases, the value of the noble metal on a load of catalyst is so high that the chemical plant rents the catalyst rather then buying it and when the catalyst is spent it is returned to the manufacturer for precious metal recovery.

Although small in quantity, consumables can add a lot of cost and complexity to a plant. The plant must be designed with systems for handling, storing, metering and disposing of all the consumables used. In many chemicals plants over half of the total pieces of equipment are associated with consumables handling.

### 6.4.6 WASTE DISPOSAL COSTS

Materials produced by the process that cannot be recycled or sold as by-products must be disposed of as waste. In some cases additional treatment is required to concentrate the waste stream before sending it to final disposal.

Hydrocarbon waste streams such as off-spec products, slop oils, spent solvents and off-gases (including hydrogen-rich gases) can often be incinerated or used as process fuel. This allows the fuel value of the stream to be recovered, and the waste stream can be assigned a value based on its heat of combustion:

$$P_{WFV} = P_F \times \Delta H_C^o \tag{6.21}$$

where:

$P_{WFV}$ = waste value as fuel (\$/lb or \$/kg)
$P_F$ = price of fuel (\$/MMBtu or \$/GJ)
$\Delta H^\circ_C$ = heat of combustion (MMBtu/lb or GJ/kg)

If additional systems such as flue gas scrubbers must be fitted to allow the waste to be combusted, then the waste stream value should be discounted to recover the extra cost.

Dilute aqueous streams are sent to waste-water treatment unless the contaminants are toxic to the bacteria in the waste-water plant. Acidic or basic wastes are neutralized prior to treatment. Neutralization is usually carried out using a base or acid that will form a solid salt that can be precipitated from the water, so that the total dissolved solids (TDS) load on the waste-water plant is not excessive. The cost of waste water treatment is typically about \$6 per 1000 gal (\$1.5/t), but there may also be local charges for spent water discharge.

Inert solid wastes can be sent to landfill at a cost of about \$50/t, or in some cases used to make roads. Wastes from neutralizing spent sulphuric acid are typically calcium sulphate (gypsum) which can be used as road fill or ammonium sulphate, which can be sold as fertilizer.

Concentrated liquid streams that cannot be incinerated locally (for example, compounds containing halogens) and non-inert solids must be disposed of as hazardous waste. This entails shipping the material to a hazardous waste company for incineration in a specialized plant or long-term storage in a suitable facility. The costs of hazardous waste disposal depend strongly on the plant location, proximity to waste disposal plants and the nature of the hazardous waste, and must be evaluated on a case-by-case basis.

Additional information on waste disposal considerations is given in Chapter 14.

### 6.4.7 LABOUR COSTS

The wages paid to plant operators and supervisors are a fixed cost of production, as described in Section 6.2.4. Almost all plants are operated on a shift-work basis (even batch plants), with typically 4.8 operators per shift position. This gives a 4-shift rotation with allowance for weekends, vacations and holidays and some use of overtime. Most plants require at least three shift positions: one operator in the control room, one outside and one in the tank farm or other feed / product shipping and receiving area. Plants that use more mechanical equipment, particularly solids handling plants, typically require more shift positions, as do plants that involve batch operations. More shift positions are also needed when handling highly toxic compounds. In some cases two or more smaller plants may be grouped together with a common control room and tank farm to reduce the number of operators needed. Very few plants run entirely unattended though, with the exception of gas processing plants, which hold no inventories of feed or product and are usually automated to allow a single control room operator to watch over several plants. A chart for estimating the minimum number of shift positions is given in Figure 6.9, but it should be emphasized that this only gives a rough guide. The design engineer should always carefully think through the operations required per shift, particularly for processes that handle solids or involve batch operations or frequent sampling.

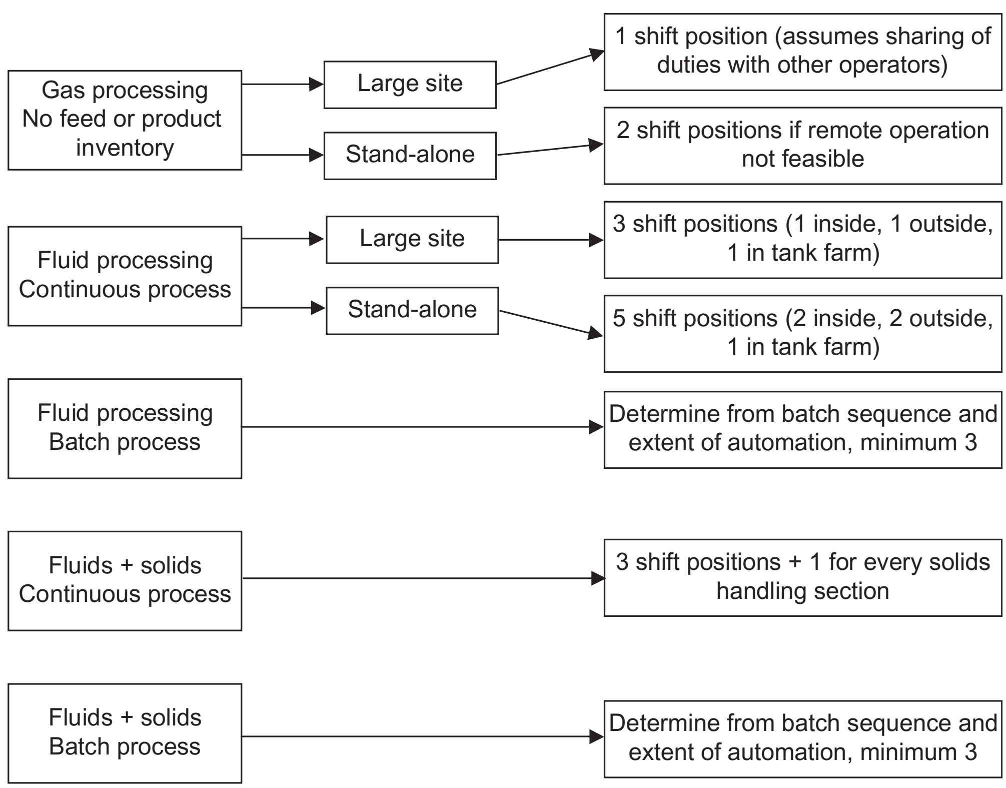



**FIGURE 6.9**

Algorithm for estimating the minimum number of shift positions.

Operator salaries vary by region and experience level. For initial estimates, an average salary of $60,000 per shift position per year on a USGC basis, not including direct or corporate overhead can be used. Supervision and overhead costs are discussed in Section 6.2.4.

### 6.4.8 BY-PRODUCT REVENUES

A good deal of process design effort is often spent analyzing by-product recovery. Potentially valuable by-products include:

1. Materials produced in stoichiometric quantities by the reactions that form the main product (see Table 6.1 for examples). If these are not recovered as by-products, then the waste disposal costs will be excessive.
2. Components that are produced in high yield by side reactions. Some examples include propylene, butylenes and butadiene, all of which are by-products of ethylene from steam cracking of naphtha feed. Orthoxylene and metaxylene are by-products of paraxylene manufacture by catalytic reforming of naphtha.
3. Components formed in high yield from feed impurities. Most sulphur is produced as a by-product of fuels manufacture. Crude oil and natural gas contain sulphur compounds that are converted to $H_2S$ during refining or gas treatment. The $H_2S$ is then converted to elemental sulphur by the Claus process. Mannitol (a valuable hexose) is made from fructose that is present in the glucose feed to the sorbitol process.
4. Components produced in low yield that have high value. Dicyclopentadiene can be recovered from the products of steam naphtha cracking. Acetophenone is recovered as a by-product of phenol manufacture, although it can also be made by oxidation of ethylbenzene or fermentation of cinnamic acid.
5. Degraded consumables such as solvents that have re-use value.

Prices for by-products can be found in the same sources used for prices of main products. The difficult part is deciding whether it is worthwhile to recover a by-product. For the by-product to have value, it must meet the specifications for that material, which may entail additional processing costs. The design engineer must therefore assess whether the additional cost of recovering and purifying the by-product is justified by the by-product value and avoided waste disposal cost, before deciding whether to value the material as a by-product or as a waste stream.

An algorithm for assessing the economic viability of recovering a by-product X is given in Figure 6.10. Note that it is important to consider not only the cost of purifying the by-product, but also whether it can be converted into something more valuable. This would include recycling the by-product within the process if that might be expected to lead to a higher yield of main product or formation of a more valuable by-product. Note also that when analyzing whether to recover a by-product the value created by recovering the by-product includes not only the revenue from by-product sales, but also the avoided by-product disposal cost. If the by-product has fuel value then the fuel value should be subtracted from the revenue instead.

A rule of thumb that can be used for preliminary screening of by-products for large plants is that for by-product recovery to be economically viable the net benefit must be greater than US$200,000 per year. The net benefit is the by-product revenue plus the avoided waste disposal cost. (This is based on the assumption that recovering by-product is going to add at least one separation to the process,

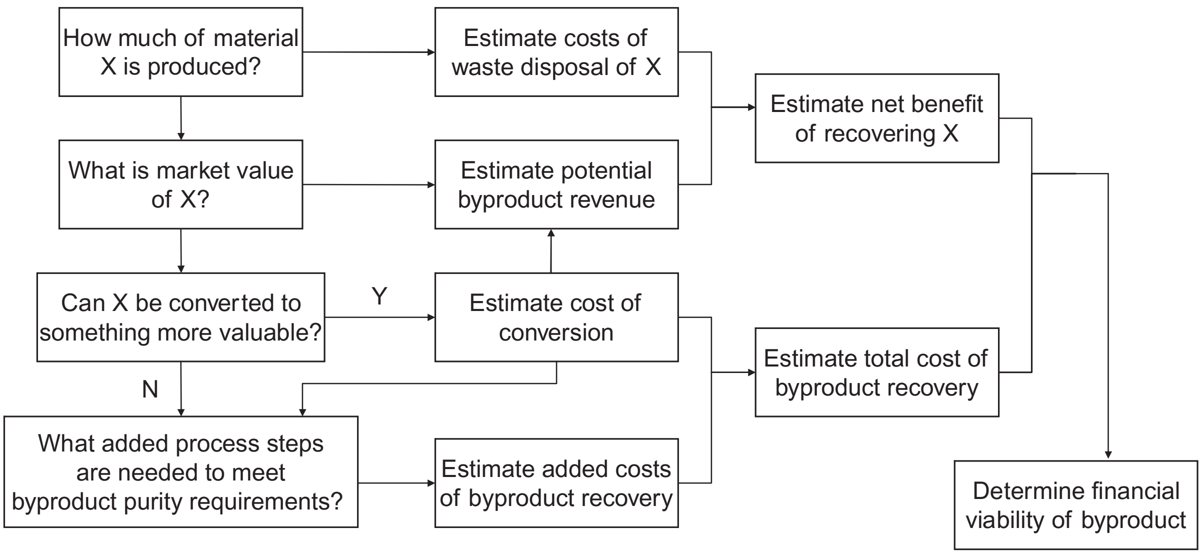



**FIGURE 6.10**

Algorithm for assessing the economic viability of by-product recovery.

which will cost at least \$0.5 million of capital, or an annualized cost of about \$170,000, as described in Section 6.7.6.).

### 6.4.9 SUMMARIZING PRODUCTION COSTS AND REVENUES

It is useful to create a single-page summary of all of the production costs and revenues associated with a project, as this makes it easier to review the project economics and understand the relative contribution of different components to the overall cost of production. The summary sheet usually lists the quantity per year and per unit production of product, the price, the cost per year and the cost per unit production of product for each of the raw materials, by-products, consumables and utilities, as well as fixed costs and capital charges.

Most chemical companies have a preferred format for summarizing costs of production, and often use standard spreadsheets. Good examples are given in the PERP reports published by Nexant (www.nexant.com/products). A template for summarizing production costs is given in Appendix G and can be downloaded in MS Excel format from the on-line material at http://books.elsevier.com/companions. The use of this template is illustrated in Example 6.11.

## 6.5 TAXES AND DEPRECIATION

The profits generated by most chemical plants are subject to taxation. Taxes can have a significant impact on the cash flows from a project. The design engineer needs to have a basic understanding of taxation and tax allowances such as depreciation in order to make an economic evaluation of the project.

### 6.5.1 TAXES

Individuals and corporations must pay income tax in most countries. The details of tax law can be complicated and governments enact changes almost every year. Companies generally retain tax specialists, either as employees or as consultants, who have deep expertise in the intricacies of the field. Such specialized knowledge is not required for engineering design projects, which are usually compared on a relatively simple after-tax basis. The design engineer may occasionally need to consult a tax expert though, particularly when comparing projects in different countries with different tax laws and investment incentives.

Information on corporate taxes can usually be found from government web sites. In the United Kingdom the main rate of corporation tax is 28% for companies with profits greater than £1.5 million per year at the time of writing. Companies with profits below this threshold are taxed at the lower Small Companies Rate (SCR) of 21%. Information on current UK taxes can be found on the HM Revenue and Customs web site at www.hmrc.gov.uk.

Information on taxes in the United States is given on the Internal Revenue Service web site at www.irs.gov. At the time of writing, the top marginal rate of federal income tax on corporations in the United States is 35%, which applies to all incomes greater than $18,333,333 (IRS Publication 542). Since almost all companies engaged in building chemical plants substantially exceed this income threshold, it is common to assume that all profits will be taxed at the marginal rate. In many locations corporations must also pay state or local income taxes.

The amount of tax that must be paid in a given year is calculated by multiplying the taxable income by the tax rate. The taxable income is given by:

$$\text{Taxable income} = \text{gross profit} - \text{tax allowances} \tag{6.22}$$

Various types of tax allowances are permitted in the tax laws of different countries, the most common of which is depreciation, discussed in Section 6.5.3. The after tax cash flow is then:

$$\begin{aligned} CF &= P - (P - D)t_r \\ &= P(1 - t_r) + Dt_r \end{aligned} \tag{6.23}$$

where:

$CF$ = after tax cash flow
$P$ = gross profit
$D$ = sum of tax allowances
$t_r$ = rate of taxation

It can be seen from equation 6.23 that the effect of tax allowances is to reduce taxes paid and increase cash flow.

In some countries, taxes are paid in a given year based on the previous year's income. This is true for the United States, where corporate taxes are based on a calendar year of operations and are due by March 15 of the following year. This complicates the calculations somewhat, but is easily coded into a spreadsheet.

## 6.5.2 INVESTMENT INCENTIVES

National and regional governments often provide incentives to encourage companies to make capital investments, since these investments create employment, generate taxation revenue and provide other benefits to politicians and the communities they represent.

The most common incentives used are tax allowances. Most countries allow some form of depreciation charge as a tax allowance, by which the fixed capital investment can be deducted from taxable income over a period of time, as described in Section 6.5.3. Other incentives that are often used include:

1. Tax waivers or vacations, in which no taxes are paid for a fixed period of time, typically two to five years after the project begins generating revenue.
2. Investment grants or credits, in which the government makes a cash contribution towards the initial investment.
3. Low cost loans, in which the government either loans capital directly or else subsidizes the interest due on a commercial loan.
4. First year allowances (FYA), in which a high proportion of the investment can be depreciated in the first year. For example, at the time of writing the U.K. government allows a 100% FYA for energy-saving or water-efficient plant and machinery (www.hmrc.gov.uk/capital_allowances/).
5. Loan guarantees, in which the government agrees to underwrite loans for the project, making it easier to secure financing on advantageous terms.

An economic comparison between different process alternatives for the same site should usually be made using the same assumptions on investment incentives. This might not always be the case though, for example, if one project is eligible for a government grant because of using renewable energy and another project is not. It should also be noted that differences in incentives can have a significant impact on investment decisions when comparing investments at a company-wide level in a global context.

## 6.5.3 DEPRECIATION CHARGES

Depreciation charges are the most common type of tax allowance used by governments as an incentive for investment. Depreciation charges are also sometimes referred to as writing down allowances (WDA). Depreciation is a non-cash charge reported as an expense, which reduces income for taxation purposes. There is no cash outlay for depreciation, and no money is transferred to any fund or account, so the depreciation charge is added back to the net income after taxes to give the total cash flow from operations.

$$\begin{aligned} CF &= I - (I \times t_r) + D \\ &= (P - D) - ((P - D) \times t_r) + D \\ &= P(1 - t_r) + Dt_r \end{aligned} \tag{6.24}$$

where:

$I$ = taxable income
$D$ = depreciation tax allowance

It can be seen that equations 6.23 and 6.24 are equivalent.

Depreciation charges can be thought of as an allowance for the "wear and tear, deterioration or obsolescence of the property" as a result of its use (IRS publ. 946).

The book value or "written down" value of an asset is the original cost paid minus the accumulated depreciation charged. The book value has no connection to the resale value or current market value of the asset.

$$\text{Book value} = \text{initial cost} - \text{accumulated depreciation} \tag{6.25}$$

Note that the law usually only allows depreciation of fixed capital investments, and not total capital, since working capital is not consumed and can be recovered at the end of the project. If land was purchased for the project, then the cost of the land must be deducted from the fixed capital cost as land is assumed to retain its value and cannot be depreciated.

Over a period of time the book value of the asset or fixed investment decreases until it is fully "paid off" or "written off", at which point depreciation can no longer be charged. The schedule of how depreciation charges are taken is set by the tax law. In a globalized economy it is necessary for design engineers to have familiarity with several different methods of depreciation, as each country has different rules. For example, the United Kingdom uses a declining balance method, while the United States uses the Modified Accelerated Cost Recovery System (MACRS) described below (IRS publication 946). When analyzing international projects the appropriate national and regional tax laws must be checked to ensure that the correct depreciation rules are followed.

There are several other less widely-used depreciation methods that are not discussed here. A good overview of these is given by Humphreys (1991).

### *Straight line depreciation*

Straight-line depreciation is the simplest method. The depreciable value, $C_d$, is depreciated over $n$ years with annual depreciation charge $D_i$ in year $i$, where:

$$D_i = \frac{C_d}{n} \text{ and } D_j = D_i \;\; \forall j \tag{6.26}$$

The depreciable value of the asset is the initial cost of the fixed capital investment, $C$, minus the salvage value (if any) at the end of the depreciable life. For chemical plants the salvage value is often taken as zero, as the plant usually continues to operate for many years beyond the end of the depreciable life.

The book value of the asset after $m$ years of depreciation, $B_m$ is:

$$\begin{aligned} B_m &= C - \sum_{i=1}^{m} D_i \\ &= C - \frac{m\, C_d}{n} \end{aligned} \tag{6.27}$$

When the book value is equal to the salvage value (or zero) then the asset is fully depreciated and no further depreciation charge can be taken.

Straight-line depreciation must be used in the United States for software (with a 36 month depreciable life), patents (with life equal to the patent term remaining) and other depreciable intangible property (IRS publ. 946).

### Declining balance depreciation

The declining-balance method is an accelerated depreciation schedule that allows higher charges in the early years of a project. This helps improve project economics by giving higher cash flows in the early years. In the declining-balance method, the annual depreciation charge is a fixed fraction, $F_d$, of the book value:

$$\begin{aligned} D_1 &= C F_d \\ B_1 &= C - D_1 = C(1 - F_d) \\ D_2 &= B_1 F = C(1 - F_d) F_d \\ B_2 &= B_1 - D_2 = C(1 - F_d)(1 - F_d) = C(1 - F_d)^2 \end{aligned} \tag{6.28}$$

Hence:

$$D_m = C(1 - F_d)^{m-1} F_d \tag{6.29}$$

$$B_m = C(1 - F_d)^m \tag{6.30}$$

The fraction $F_d$ must be less than $2/n$, where $n$ is the depreciable life in years. When $F_d = 2/n$, this method is known as double declining-balance depreciation.

At the time of writing, the United Kingdom uses declining balance depreciation with rates of 4% for buildings and structures, 25% for plant and machinery and 6% for long-life assets (see www.hmrc.gov.uk/capital_allowances for details).

### Modified Accelerated Cost Recovery System (MACRS)

The MACRS depreciation method was established by the U.S. Tax Reform Act of 1986 and is the depreciation method used for most tangible assets in the U.S.A. The details of the MACRS depreciation method are given in IRS publication 946, which is available online at www.irs.gov/publications. The method is basically a combination of the double declining-balance method and the straight-line method. The double declining-balance method is used until the depreciation charge becomes less than it would be under the straight-line method, at which point the MACRS method switches to charge the same amount as the straight-line method.

Under MACRS depreciation, different recovery periods are assigned to different kinds of asset, based on a usable life ("class life") designated by the U.S. Internal Revenue Service (IRS). For chemical plants the class life is 9.5 years and the recovery period is five years. The class life for other process industries ranges from 7.5 years for offshore oil platforms to 18 years for coal gasification; see Appendix B of IRS publication 946. It should also be noted that for roads, docks and other civil infrastructure a 15 year recovery period is used, so some offsite investments are depreciated on a different schedule from that used for the ISBL investment.

Another important convention within MACRS depreciation is that the method assumes that all property is acquired mid-year and hence assigns half of the full year depreciation in the first and last years of the recovery period. The result is the schedule of depreciation charges given in Table 6.9.

There are other details of MACRS depreciation that are not discussed here, and at the time of writing the tax law also allows assets to be depreciated by the straight-line method (over the class life, not the recovery period and still following the half-year convention). The U.S. tax law is revised frequently and the most recent version of IRS publication 946 should be consulted for the current regulations.

**Table 6.9 MACRS depreciation charges**

| Recovery year | Depreciation rate ($F_i = D_i/C_d$) Five-year recovery | Fifteen-year recovery |
|---|---|---|
| 1 | 20.00 | 5.00 |
| 2 | 32.00 | 9.50 |
| 3 | 19.20 | 8.55 |
| 4 | 11.52 | 7.70 |
| 5 | 11.52 | 6.93 |
| 6 | 5.76 | 6.23 |
| 7 | | 5.90 |
| 8 | | 5.90 |
| 9 | | 5.91 |
| 10 | | 5.90 |
| 11 | | 5.91 |
| 12 | | 5.90 |
| 13 | | 5.91 |
| 14 | | 5.90 |
| 15 | | 5.91 |
| 16 | | 2.95 |

## EXAMPLE 6.8

A chemical plant with a fixed capital investment of $100 million generates an annual gross profit of $50 million. Calculate the depreciation charge, taxes paid and after-tax cash flows for the first ten years of plant operation using straight-line depreciation over 10 years and using MACRS depreciation with a five year recovery period. Assume the plant is built at time zero and begins operation at full rate in year 1. Assume the rate of corporate income tax is 35% and taxes must be paid based on the previous year's income.

### Solution

The solution is easily coded into a spreadsheet. The results are shown in the tables below:

| Year | Gross Profit (MM$) | Depreciation Charge (MM$) | Taxable Income (MM$) | Taxes Paid (MM$) | Cash Flow (MM$) |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | –100 |
| 1 | 50 | 10 | 40 | 0 | 50 |
| 2 | 50 | 10 | 40 | 14 | 36 |
| 3 | 50 | 10 | 40 | 14 | 36 |
| 4 | 50 | 10 | 40 | 14 | 36 |
| 5 | 50 | 10 | 40 | 14 | 36 |
| 6 | 50 | 10 | 40 | 14 | 36 |
| 7 | 50 | 10 | 40 | 14 | 36 |
| 8 | 50 | 10 | 40 | 14 | 36 |
| 9 | 50 | 10 | 40 | 14 | 36 |
| 10 | 50 | 10 | 40 | 14 | 36 |

| Year | Gross Profit (MM$) | Depreciation Charge (MM$) | Taxable Income (MM$) | Taxes Paid (MM$) | Cash Flow (MM$) |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | –100 |
| 1 | 50 | 20 | 30 | 0 | 50 |
| 2 | 50 | 32 | 18 | 10.50 | 39.50 |
| 3 | 50 | 19.2 | 30.8 | 6.30 | 43.70 |
| 4 | 50 | 11.52 | 38.48 | 10.78 | 39.22 |
| 5 | 50 | 11.52 | 38.48 | 13.47 | 36.53 |
| 6 | 50 | 5.76 | 44.24 | 13.47 | 36.53 |
| 7 | 50 | 0 | 50 | 15.48 | 34.52 |
| 8 | 50 | 0 | 50 | 17.50 | 32.50 |
| 9 | 50 | 0 | 50 | 17.50 | 32.50 |
| 10 | 50 | 0 | 50 | 17.50 | 32.50 |

## 6.6 PROJECT FINANCING

The construction and operation of chemical plants require large amounts of capital. Corporations engaged in the production of chemicals must raise the finances to support such investments. Like taxation, corporate financing is a specialized subject with many intricacies that require expert knowledge. The design engineer needs a superficial awareness of this subject to carry out economic analysis and optimization of the design.

### 6.6.1 BASICS OF CORPORATE ACCOUNTING AND FINANCE

The purpose of financial accounting is to report the economic performance and financial condition of a company to its owners (shareholders), lenders, regulatory agencies and other stakeholders. The primary means for financial reporting is the annual report to shareholders. The annual reports for companies in the chemical, life sciences and fuels industries generally contain:

1. A letter from the Chief Executive Officer (CEO) describing the past year's operations, significant acquisitions, divestitures and restructuring, and plans for the short and long term.
2. Financial information:
   a. Balance sheet
   b. Income statement
   c. Cash flow statement
   d. Notes to the financial statements
   e. Comments from the independent auditors.
3. Information on the directors and executive management of the company.
4. A report on the health, safety and environmental performance of the company (sometimes published separately).

The annual report of any publicly traded company will usually be available on-line and can easily be found by visiting the company's web site. The site will usually have a prominent link to "information for investors" or something similar. No attempt has been made to create fictitious financial statements for the purposes of this book as an abundance of real examples is readily available on-line. The reader is encouraged to search the web for real examples.

### *Balance sheet*

The balance sheet is a snapshot of the financial condition of the company. It lists all the assets owned by the company and all the liabilities or amounts owed by the company. The difference between assets and liabilities is the stockholder's equity, i.e., notionally the amount of money the stockholders would have available to share out if they decided to liquidate the company.

$$\text{Stockholder's equity} = \text{assets} - \text{liabilities} \tag{6.31}$$

Assets are typically listed in order of decreasing liquidity. Liquidity is a measure of how easily the asset could be turned into cash. Assets include:

- Cash and cash equivalents.
- Notes and accounts receivable, i.e., money owed to the company for goods shipped but not yet paid for.
- Inventories of raw materials, products, spare parts and other supplies.
- Prepaid taxes and expenses.
- Investments such as equity stakes in other companies or joint ventures.
- Property, plant and equipment. This is listed at book value, i.e., cost less accumulated depreciation. The actual market value of these assets may be considerably higher.
- Intangible assets such as patents, trademarks, goodwill, etc.

Liabilities are usually listed in the order in which they are due, starting with current liabilities. Liabilities include:

- Accounts payable, i.e., payment owed on goods already received by the company.
- Notes and loans that are due for repayment.
- Accrued liabilities and expenses such as legal settlements, amounts set aside for warranties, guarantees, etc.
- Deferred income taxes.
- Long term debt.

The difference between assets and liabilities is the shareholder's equity. This consists of the capital paid in by the owners of common and preferred stocks, together with earnings retained and reinvested in the business. The capital paid in by the shareholders is often listed as the par value of the stock (typically 25¢ to $1 per share) plus the additional capital paid in when the stock was initially sold by the company. Note that this reflects only the capital raised by the company and has no relation to subsequent increases or decreases in the value of the stock that may have resulted from trading.

### *Income statement*

The income statement or consolidated statement of operations is a summary of the incomes, expenditures and taxes paid by the company over a fixed period of time. Results are usually presented for the past three calendar years.

The income statement lists the following items:

1. Sales and operating revenues (positive).
2. Income from equity holdings in other companies (positive).
3. Cost of goods sold (negative).
4. Selling, general and administrative expenses (negative).
5. Depreciation (negative on the income statement, but will be added back on the cash flow statement)
6. Interest paid on debt (negative).
7. Taxes other than income tax, such as excise duties (negative).
8. Income taxes (negative).

The sum of items 1 through 5 is sometimes listed as earnings before interest and taxes (EBIT). The sum of items 1 through 7 is listed as income before taxes or taxable income, and is usually positive. The net income is the sum of items 1 through 8, i.e., income before taxes minus taxes paid. Net income is also usually expressed as earnings per share of common stock.

The income statement gives a good insight into the overall profitability and margins of a business. It has to be read carefully though, as several items listed are non-cash charges such as depreciation, that do not affect the cash flow of the business. Corrections for these items are made in the cash flow statement.

### *Cash flow statement*

The cash flow statement gives a summary of overall cash flows into and out of the business as a result of operating activities, investments and financing activities. It is also usually reported for the past three calendar years.

The cash flow from operating activities section starts with the net income. Adjustments are made for non-cash transactions (depreciation and deferred taxes are added back in), and changes in assets and liabilities.

The cash flow from investing activities section lists the cash spent on acquiring fixed assets such as property, plant and equipment, less any revenues from sale of fixed assets. It also lists acquisitions or divestitures of subsidiary businesses.

The cash flow from financing activities section summarizes changes in the company's long-term and short-term debt, proceeds from issues of common stock, repurchase of stocks, and dividends paid to stockholders.

The sum of cash flows from operations, investments and financing gives the net change in cash and cash equivalents. This is then added to the cash and cash equivalents from the beginning of the year to give the cash and cash equivalents at the end of the year, which appears on the balance sheet.

### *Summary*

The business and accounting literature contains a wealth of information on how to read and analyze corporate financial statements. Most engineers work for or with corporations and have a direct personal interest in understanding financial performance; however, a detailed treatment of the subject is beyond the scope of this book. Excellent introductions to finance and accounting are given in the books by Spiro (1996) and Shim and Henteleff (1995).

### 6.6.2 DEBT FINANCING AND REPAYMENT

Most debt capital is raised by issuing long-term bonds. A mortgage is a bond that is backed by pledging a specific real asset as security against the loan. An unsecured bond is called a debenture. The ratio of total debt divided by total assets is known as the debt ratio (*DR*) or leverage of the company.

All debt contracts require payment of interest on the loan and repayment of the principal (either at the end of the loan period or amortized over the period of the loan). Interest payments are a fixed cost, and if a company defaults on these payments then its ability to borrow money will be drastically reduced. Since interest is deducted from earnings, the greater the leverage of the company, the higher is the risk to future earnings, and hence to future cash flows and the financial solvency of the company. In the worst case, the company could be declared bankrupt and the assets of the company sold off to repay the debt. Finance managers therefore carefully adjust the amount of debt owed by the company so that the cost of servicing the debt (the interest payments) does not place an excessive burden on the company.

The rate of interest owed on debt depends on the bond markets, government central banks and the credit worthiness of the company. When new bonds are issued, they must be offered at a competitive interest rate, otherwise they will not sell. If the bond issuer has a high credit rating then they will be able to issue bonds at close to the interest rates set by the government. (U.S. Treasury bonds are not rated, as it is assumed that they will be backed by the United States Federal Government. Some other countries' bonds are also not rated.) If the credit rating of the issuer is lower, then there is a higher chance that the debt may not be repaid, in which case it must be offered at a higher interest rate to offset this risk. Credit rating services such as Moody's and Standard and Poor's study the finances of corporations and publish credit ratings. These ratings are usually not advertised by issuers unless they are very high, but they are published in the financial papers. The difference in interest rate between low-rated and high-rated bonds issued at the same time is typically 2 to 3%.

Once they have been issued, bonds are traded on financial exchanges such as the London Stock Exchange, the New York Stock Exchange or the American Stock Exchange. Although the price of the bond in subsequent trading may vary from the offer price (or face value), the interest rate remains fixed. The financial newspapers report prices daily for the most actively traded corporate bonds. Bond prices can also be found at www.investinginbonds.com, together with much other useful information on bond markets. The interest rate is listed as the "coupon" and the date on which the bond expires is the "maturity". Bonds are also assigned a unique nine-digit identification number by the American Bankers' Association Committee on Uniform Security Identification Procedures (CUSIP). For example, in 2006 Honeywell Inc. issued a 30-year bond CUSIP #438516AR7 with coupon 5.700 and maturity 03/15/2036.

### 6.6.3 EQUITY FINANCING

Equity capital consists of the capital contributed by stockholders, together with earnings retained for reinvestment in the business. Stockholders purchase stocks in the expectation of getting a return on their investment. This return can come from the dividends paid annually to stockholders (the part of earnings returned to the owners) or from growth of the company that is recognized by the stock market and leads to an increase in the price of the stock. Most stock is usually held by sophisticated institutional investors such as banks, mutual funds, insurance companies and pension funds. These investors employ expert analysts to assess the performance of companies relative to other companies in the same sector, and to the market as a whole. If the management of a company does not effectively deliver the financial return expected by investors, the stock price will suffer and the management will soon be replaced.

Simple measures of the effectiveness of management are the return on equity and earnings per share. Return on equity (ROE) is defined as:

$$\text{ROE} = \frac{\text{net annual profit}}{\text{stockholders' equity}} \times 100\% \tag{6.32}$$

The stockholders' expectation of return on their equity can be expressed as an interest rate and is known as the cost of equity capital. The cost of equity required to meet the expectations of the market is usually substantially higher than the interest rate owed on debt, because of the riskier nature of equity finance (since debt holders are paid first and hence have the primary right to any profit made by the business). For most corporations in the European Union and United States at the time of writing the cost of equity is in the range 25% to 30%.

### 6.6.4 COST OF CAPITAL

Very few companies operate entirely on debt or equity financing alone and most use a balance of both. The overall cost of capital is simply the weighted average of the cost of debt and the cost of equity.

$$i_c = (DR \times i_d) + ((1 - DR) \times i_e) \tag{6.33}$$

where:

$i_c$ = cost of capital
$DR$ = debt ratio
$i_d$ = interest rate due on debt
$i_e$ = cost of equity

For example, if a company were financed 55% with debt at an average 8% interest and 45% with equity that carried an expectation of a 25% return, then the overall cost of capital would be:

$$i_c = (0.55 \times 0.08) + (0.45 \times 0.25)$$
$$\underline{\underline{= 0.1565}}$$

Since the equity is by definition (equation 6.31) the assets minus the liabilities (debt), the overall return on assets (ROA) can be expressed as:

$$\text{ROA} = \frac{\text{net annual profit}}{\text{total assets}} \times 100\% \tag{6.34}$$

It follows that:

$$\frac{\text{ROA}}{\text{ROE}} = \frac{\text{stockholders' equity}}{\text{total assets}} = 1 - DR \tag{6.35}$$

The overall cost of capital sets the interest rate that is used in economic evaluation of projects. The total portfolio of projects funded by a company must meet or exceed this interest rate if the company is to achieve its targeted return on equity and hence satisfy the expectations of its owners.

## 6.7 ECONOMIC EVALUATION OF PROJECTS

As the purpose of investing money in a chemical plant is to earn money, some means of comparing the economic performance of projects is needed. Before a company agrees to spend a large amount of capital on a proposed project, the management must be convinced that the project will provide a sound investment compared to other alternatives. This section introduces the principal methods used for making economic comparisons between projects.

### 6.7.1 CASH FLOW AND CASH FLOW DIAGRAMS

During any project, cash initially flows out of the company to pay for the costs of engineering, equipment procurement and plant construction. Once the plant is constructed and begins operation, then the revenues from sale of product begin to flow into the company. The "net cash flow" at any time is the difference between the earnings and expenditure. A cash-flow diagram, such as that shown in Figure 6.11, shows the forecast cumulative net cash flow over the life of a project. The cash flows are based on the best estimates of investment, operating costs, sales volume and sales price that can be made for the project. A cash-flow diagram gives a clear picture of the resources required for a project and the timing of the earnings. The diagram can be divided into the following characteristic regions:

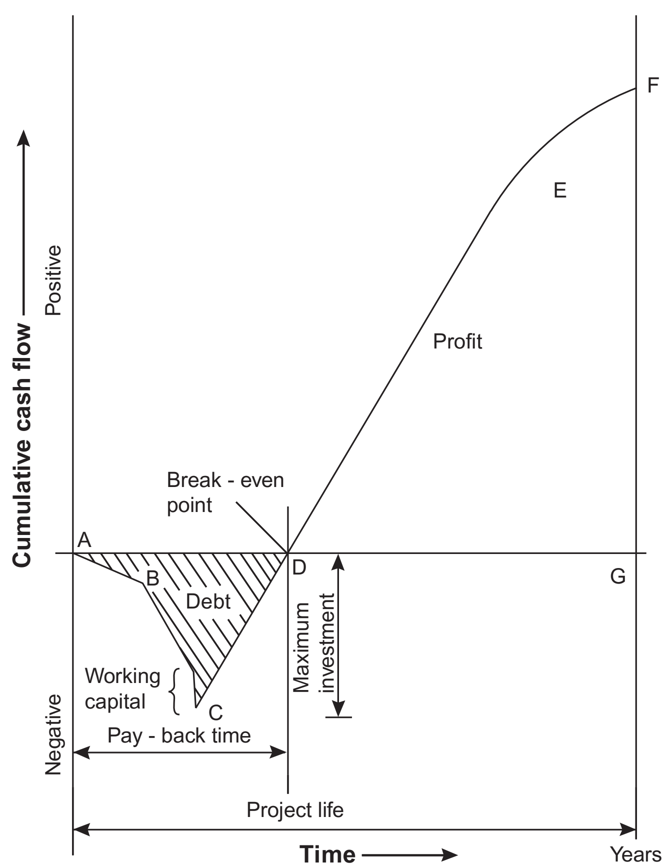



**FIGURE 6.11**

Project cash-flow diagram.

A–B The investment required to design the plant.

B–C The heavy flow of capital to build the plant and provide funds for start-up, including working capital.

C–D The cash-flow curve turns up at C, as the process comes on stream and income is generated from sales. The net cash flow is now positive but the cumulative amount remains negative until the investment is paid off, at point D.

Point D is known as the *break-even point* and the time to reach the break-even point is called the *pay-back time*. (In a different context, the term "break-even point" is also sometimes used for the percentage of plant capacity at which the income equals the cost of production).

D–E In this region the cumulative cash flow is positive. The project is earning a return on the investment.

E–F Toward the end of project life the rate of cash flow may tend to fall off, due to increased operating costs and falling sales volume and price due to obsolescence of the plant, and the slope of the curve changes.

The point F gives the final cumulative net cash flow at the end of the project life.

Net cash flow is a relatively simple and easily understood concept, and forms the basis for the calculation of other, more complex, measures of profitability. Taxes and the effect of depreciation are usually not considered in cash flow diagrams.

## 6.7.2 SIMPLE METHODS FOR ECONOMIC ANALYSIS

### *Pay-back time*

A simple method for estimating the pay-back time is to divide the total initial capital (fixed capital plus working capital) by the average annual cash flow:

$$\text{simple pay-back time} = \frac{\text{total investment}}{\text{average annual cash flow}} \tag{6.36}$$

This is not the same pay-back time indicated by the cash-flow diagram, as it assumes that all the investment is made in year zero and revenues begin immediately. For most chemical plant projects, this is not realistic as investments are typically spread over one to three years and revenues may not reach 100% of design basis until the second year of operation. The simple pay-back time also neglects taxes and depreciation.

### *Return on investment*

Another simple measure of economic performance is the return on investment, ROI. The ROI is defined in a similar manner to ROA and ROE:

$$\text{ROI} = \frac{\text{net annual profit}}{\text{total investment}} \times 100\% \tag{6.37}$$

If ROI is calculated as an average over the whole project then:

$$\text{ROI} = \frac{\text{cumulative net profit}}{\text{plant life} \times \text{initial investment}} \times 100\% \tag{6.38}$$

Calculation of the after-tax ROI is complicated if the depreciation term is less than the plant life and if an accelerated method of depreciation such as declining balance or MACRS is used. In such cases, it is just as easy to calculate one of the more meaningful economic criteria such as net present value or discounted cash flow rate of return, described below. Because of this complication, a pre-tax ROI is often used instead:

$$\text{pre-tax ROI} = \frac{\text{pre-tax cash flow}}{\text{total investment}} \times 100\% \tag{6.39}$$

Note that pre-tax ROI is based on cash flow, not profit or taxable income, and therefore does not include a depreciation charge.

Return on investment is also sometimes calculated for incremental modifications to a large project, as described in Section 6.9.3.

### 6.7.3 TIME VALUE OF MONEY

In Figure 6.11 the net cash flow is shown at its value in the year in which it occurred. So the numbers on the ordinate show the "future worth" of the project. The cumulative value is the "net future worth" (NFW).

The money earned in any year can be reinvested as soon as it is available and can start to earn a return. So money earned in the early years of the project is more valuable than that earned in later years. This "time value of money" can be allowed for by using a variation of the familiar compound interest formula. The net cash flow in each year of the project is brought to its "present value" at the start of the project by discounting it at some chosen compound interest rate.

The future worth of an amount of money, $P$, invested at interest rate, $i$, for $n$ years is:

$$\text{Future worth in year } n = P(1+i)^n$$

Hence the present value of a future sum is:

$$\text{present value of future sum} = \frac{\text{future worth in year } n}{(1+i)^n} \tag{6.40}$$

The interest rate used in discounting future values is known as the discount rate and is chosen to reflect the earning power of money. In most companies the discount rate is set at the cost of capital (see Section 6.6.4).

Discounting of future cash flows should not be confused with allowing for price inflation. Inflation is a general increase in prices and costs, usually caused by imbalances between supply and demand. Inflation raises the costs of feed, products, utilities, labour and parts, but does not affect depreciation charges, which are based on original cost. Discounting, on the other hand, is a means of comparing the value of money that is available now (and can be reinvested) with money that will become available at some time in the future. All of the economic analysis methods can be modified to allow for inflation. See, for example, Humphreys (1991), Chapter 6. In practice, most companies assume that although prices may suffer inflation, margins and hence cash flows will be relatively insensitive to inflation. Inflation can therefore be neglected for the purposes of comparing the economic performance of projects.

### 6.7.4 NET PRESENT VALUE

The net present value (NPV) of a project is the sum of the present values of the future cash flows:

$$\text{NPV} = \sum_{n=1}^{n=t} \frac{CF_n}{(1+i)^n} \tag{6.41}$$

where:

$CF_n$ = cash flow in year $n$
$t$ = project life in years
$i$ = interest rate (= cost of capital, percent /100)

The net present value is always less than the total future worth of the project because of the discounting of future cash flows. Net present value is easily calculated using spreadsheets and most spreadsheet programs have a NPV function.

The net present value is a strong function of the interest rate used and the time period studied. When different time periods are analyzed the time period is sometimes denoted by a subscript. For example, $NPV_{10}$ would denote the NPV over a 10-year period.

Net present value is a more useful economic measure than simple pay-back and ROI, since it allows for the time value of money and also for annual variation in expenses and revenues. Few large projects are completed in a single year and immediately begin production at full capacity. A more typical start-up schedule is given in Table 6.10. Net present value is also a more appropriate method to use when considering after-tax income using an accelerated depreciation method such as declining balance or MACRS.

## 6.7.5 DISCOUNTED CASH-FLOW RATE OF RETURN (DCFROR)

By calculating the NPV at various interest rates, it is possible to find an interest rate at which the cumulative net present value at the end of the project is zero. This particular rate is called the "discounted cash-flow rate of return" (DCFROR) and is a measure of the maximum interest rate that the project could pay and still break even by the end of the project life.

$$\sum_{n=1}^{n=t} \frac{CF_n}{(1+i')^n} = 0 \tag{6.42}$$

**Table 6.10 Typical start-up schedule**

| Year | Costs | Revenues | Explanation |
|---|---|---|---|
| 1st year | 30% of fixed capital | 0 | Engineering + long lead-time items |
| 2nd year | 40 – 60% of fixed capital | 0 | Procurement and construction |
| 3rd year | 10 – 30% of fixed capital + working capital | | Remaining construction |
| | + FCOP + 30% VCOP | 30% of design basis revenue | Initial production |
| 4th year | FCOP + 50-90% VCOP | 50 – 90% of design basis revenue | Shake-down of plant |
| 5th year + | FCOP + VCOP | 100% of design basis revenue | Full production at design rates |

where:

$CF_n$ = cash flow in year $n$
$t$ = project life in years
$i'$ = the discounted cash flow rate of return (percent /100)

The value of $i'$ is found by trial-and-error calculations or by using the appropriate function in a spreadsheet. A more profitable project will be able to pay a higher DCFROR.

DCFROR provides a useful way of comparing the performance of capital for different projects, independent of the amount of capital used, the life of the plant, or the actual interest rates prevailing at any time. DCFROR is a more useful method than NPV when comparing projects of very different size. The NPV of large projects is usually greater than that of small projects, but then the investment is also much greater. DCFROR is independent of project size and the project with the highest DCFROR always provides the best "bang for the buck". When DCFROR is used as an investment criterion, companies usually expect projects to have a DCFROR greater than the cost of capital.

DCFROR can also be compared directly with interest rates. Because of this, it is sometimes known as the interest rate of return or internal rate of return (IRR).

## EXAMPLE 6.9

Estimate the NPV at a 12% interest rate and the DCFROR for the project described in Example 6.8, using the MACRS depreciation method.

### Solution

Calculating the present values of the cash flows from the previous example requires adding two columns to the spreadsheet. We first calculate the discount factor $(1 + i)^{-n}$, and then multiply this by the cash flow in year $n$ to give the present value of the cash flow. The present values can then be summed to give the net present value:

| Year | Gross Profit (MM$) | Depreciation Charge (MM$) | Taxable Income (MM$) | Taxes Paid (MM$) | Cash Flow (MM$) | Discount Factor | Present Value of CF (MM$) |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | –100 | 1 | –100 |
| 1 | 50 | 20 | 30 | 0 | 50 | 0.893 | 44.64 |
| 2 | 50 | 32 | 18 | 10.50 | 39.50 | 0.797 | 31.49 |
| 3 | 50 | 19.2 | 30.8 | 6.30 | 43.70 | 0.712 | 31.10 |
| 4 | 50 | 11.52 | 38.48 | 10.78 | 39.22 | 0.636 | 24.93 |
| 5 | 50 | 11.52 | 38.48 | 13.47 | 36.53 | 0.567 | 20.73 |
| 6 | 50 | 5.76 | 44.24 | 13.47 | 36.53 | 0.507 | 18.51 |
| 7 | 50 | 0 | 50 | 15.48 | 34.52 | 0.452 | 15.61 |
| 8 | 50 | 0 | 50 | 17.50 | 32.50 | 0.404 | 13.13 |
| 9 | 50 | 0 | 50 | 17.50 | 32.50 | 0.361 | 11.72 |
| 10 | 50 | 0 | 50 | 17.50 | 32.50 | 0.322 | 10.46 |
| | | | | | | | |
| | | | | Interest rate | | 12.00% | |
| | | | | Total = Net present value = | | | 122.32 |

Note that we could also have calculated NPV directly using the NPV function. In MS Excel, the NPV function starts at the end of year 1, so any cash flows in year 0 should not be included in the function range.

The DCFROR can then be found by adjusting the interest rate until the NPV is equal to zero. This is easily accomplished in the spreadsheet using the "Goal Seek" tool, giving DCFROR = 40.9%.

### 6.7.6 ANNUALIZED COST METHODS

An alternative method of comparing the magnitude of a capital investment in current dollars with a revenue stream in the future is to convert the capital cost into a future annual capital charge.

If an amount $P$ is invested at an interest rate $i$, then after $n$ years of compound interest it matures to the sum $P\ (1 + i)^n$.

If, instead, an amount $A$ is invested each year, also at interest rate $i$, then it matures to a sum, S, where:

$$S = A + A(1+i) + A(1+i)^2 + \cdots + A(1+i)^{n-1} \tag{6.43}$$

so

$$S(1+i) = A(1+i) + A(1+i)^2 + \cdots + A(1+i)^n \tag{6.44}$$

Hence, subtracting equation 6.43 from equation 6.44:

$$S\,i = A[(1+i)^n - 1] \tag{6.45}$$

If the annual payments $A$ have matured to give the same final sum that would have been obtained by investing the principal $P$ at the same interest rate then:

$$S = P(1+i)^n = \frac{A}{i}\,[(1+i)^n - 1]$$

Hence:

$$A = P\,\frac{[i\ (1\ +\ i)^n]}{[(1\ +\ i)^n\ -\ 1]} \tag{6.46}$$

and we can define an annual capital charge ratio, $ACCR$, as:

$$ACCR = \frac{A}{P} = \frac{[i\ (1\ +\ i)^n]}{[(1\ +\ i)^n\ -\ 1]} \tag{6.47}$$

The annual capital charge ratio is the fraction of the principal that must be paid out each year to fully repay the principal and all accumulated interest over the life of the investment. This is the same formula used for calculating payments on home mortgages and other loans where the principal is amortized over the loan period.

If the cost of capital is used as the interest rate (see Section 6.6.4), then the annual capital charge ratio can be used to convert the initial capital expense into an annual capital charge, or annualized capital cost, as described in Section 6.2.5.

$$\text{Annual capital charge (ACC)} = ACCR \times \text{total capital cost} \tag{6.48}$$

The annual capital charge can be added to the operating costs to give a total annualized cost, TAC:

$$\text{TAC} = \text{operating costs} + ACCR\ \ \text{total capital cost} \tag{6.49}$$

The TAC can be compared with forecasted future revenues. The TAC is also sometimes referred to as total cost of production or TCOP.

Table 6.11 shows values of $ACCR$ for different values of $i$ and $n$. For a typical cost of capital of about 15% and a plant life of ten years the value of $ACCR$ is 0.199, or about one-fifth of the capital investment.

**Table 6.11 Values of annual capital charge ratio (*ACCR*) for different interest rates**

| Interest rate, *i* | *ACCR:* 10 year life | *ACCR:* 20 year life |
|---|---|---|
| 0.1 | 0.163 | 0.117 |
| 0.12 | 0.177 | 0.134 |
| 0.15 | 0.199 | 0.16 |
| 0.2 | 0.239 | 0.205 |
| 0.25 | 0.280 | 0.253 |
| 0.3 | 0.323 | 0.302 |

There are a few important things that should be noted when using the annualized cost method:

1. The method assumes investment and cash flows begin immediately, and so does not capture information on the timing of early expenditures and revenues.
2. The method does not take into account taxes or depreciation, and assumes that all of the revenue from the project is available to provide a return on the initial investment.
3. Working capital is recovered at the end of the project and so strictly only the fixed capital should be annualized. Equations 6.46 and 6.47 can be modified for the case where an additional sum becomes available at the end of the investment term, but this modified version is seldom used in practice and working capital is often either neglected in the annualized cost method or else (wrongly) thrown in with fixed capital. A simple way around this problem is to assume that the working capital is entirely funded by debt, in which case the cost of carrying the working capital is reduced to an interest payment that appears as part of the fixed costs of production. At the end of the project life the working capital will be released and will be available to repay the principal on the debt.
4. As described in Section 6.2.4, several of the fixed costs of production are proportional to the fixed capital invested (*FC*). If we assume annual charges of 3% of *FC* for maintenance, 2% of *FC* for property tax and 65% plant overhead then the annual capital charge ratio is increased by $0.02 + (1.65 \times 0.03) = 0.07$.
5. If we also assume engineering costs are 10% of (ISBL + OSBL) capital investment and add 15% of (ISBL + OSBL) capital as contingency, then with a 10 year plant life and a 15% interest rate the annual capital charge ratio is:

$$\begin{aligned} ACCR &= [0.199 \times (1.0 + 0.1 + 0.15) + 0.07] \times [\text{Installed ISBL} + \text{OSBL capital cost}] \\ &= 0.32 \times [\text{Installed ISBL} + \text{OSBL capital cost}] \end{aligned} \tag{6.50}$$

Equation 6.50 is the basis for the widely-used rule of thumb of annualizing capital cost by dividing by three. When using this rule of thumb, it is important to remember that some, but not all, of the fixed costs have been counted in the annual capital charge.

The annualized cost method involves more assumptions than calculating NPV or DCFROR, but it is widely used as a quick way of comparing investments with the resulting benefits. Annualized cost is also useful as a method for analyzing small projects and modifications that lead to reduced operating costs (for example, heat recovery projects), since the annualized capital outlay can be directly traded off against the expected annual savings and there is usually no change in working capital, operating labour or other fixed costs of production. Small projects usually can be executed quickly, so the error introduced by neglecting the timing of investments and revenues is less important than it is when designing a new plant.

The annualized cost method is also used when comparing the costs of equipment with different expected operating life. Annualization of the costs allows equipment with different service life to be compared on the same annual basis. This is illustrated in the example that follows.

### EXAMPLE 6.10

A carbon steel heat exchanger that costs €140,000 is expected to have a service life of five years before it requires replacement. If type 304 stainless steel is used then the service life will be increased to 10 years. Which exchanger is the most economical if the cost of capital is 12%?

**Solution**

With a 12% interest rate and five year life, the annual capital charge ratio is

$$ACCR = \frac{[i(1+i)^n]}{[(1+i)^n - 1]} = \frac{\left[0.12(1.12)^5\right]}{\left[(1.12)^5 - 1\right]} = 0.277 \tag{6.47}$$

The annualized capital cost of the carbon steel exchanger is then = €140,000 × 0.277 = €38,780 /y

From Table 6.5, we can estimate the cost of the type 304 stainless steel exchanger to be €140,000 × 1.3 = €182,000. From Table 6.11 (or equation 6.47), with a ten year life and 12% interest rate the annual capital charge ratio is 0.177, so the annualized cost of the stainless steel exchanger is:

$$= €182{,}000 \times 0.177 = €32{,}210/\text{y}$$

In this case, it would be more economical to buy the stainless steel heat exchanger.

## 6.7.7 SUMMARY

There is no single best criterion for economic evaluation of projects. Each company uses its own preferred methods and sets criteria for the minimum performance that will allow a project to be funded (see Section 6.9). The design engineer must be careful to ensure that the method and assumptions used are in accordance with company policy, and that projects are compared on a fair basis. Projects should always be compared using the same economic criterion, but do not have to be compared on *the exact same* basis, since in a global economy there may be significant regional advantages in feed and product pricing, capital costs, financing or investment incentives.

As well as economic performance, many other factors have to be considered when evaluating projects; such as those listed below:

1. Safety.
2. Environmental problems (waste disposal).
3. Political considerations (government policies).
4. Location of customers and suppliers (supply chain).
5. Availability of labour and supporting services.
6. Corporate growth strategies.
7. Company experience in the particular technology.

Project selection is discussed in more detail in Section 6.9.

## EXAMPLE 6.11

Adipic acid is used in the manufacture of nylon 6,6. It is made by hydrogenation of phenol to a mixture of cyclohexanol and cyclohexanone (known as KA oil – ketone and alcohol), followed by oxidation with nitric acid. The overall reaction can be written approximately as:

$$C_6H_5OH + 2H_2 \rightarrow C_6H_{10}O$$

$$C_6H_{10}O + H_2 \rightarrow C_6H_{11}OH$$

$$C_6H_{11}OH + 2HNO_3 \rightarrow HOOC(CH_2)_4COOH + N_2O + 2H_2O$$

The actual process requirements of phenol, hydrogen, nitric acid and utilities and consumables have been determined to be:

| Material | Amount | Units |
|---|---|---|
| Phenol | 0.71572 | lb/lb product |
| Hydrogen | 0.0351 | lb/lb product |
| Nitric acid (100% basis) | 0.71778 | lb/lb product |
| By-product off gas | 0.00417 | lb/lb product |
| Various catalysts and chemicals | 32.85 | $/metric ton product |
| Electric power | 0.0939 | kWh/lb product |
| Cooling water | 56.1 | gal/lb product |
| HP steam | 0.35 | lb/lb product |
| MP steam | 7.63 | lb/lb product |
| Boiler feed water | 0.04 | gal/lb product |

These yields were taken from Chem Systems PERP report 98/99-3 Adipic acid (Chem Systems, 1999). The nitric acid consumption is given on a 100% basis, but 60% nitric acid is used in the process.

Estimate the fixed capital cost, the working capital, the cash cost of production and total cost of production for a new 400,000 metric ton per year (400 kt/y) adipic acid plant located in Northeast Asia. The prices of adipic acid, phenol, hydrogen and nitric acid have been forecasted for Northeast Asia as $1400/t, $1000/t, $1100/t and $380/t respectively. Assume a 15% cost of capital and a 10 year project life.

### Solution

It is convenient to summarize costs of production in a spreadsheet, as discussed in Section 6.4.9. The template from Appendix G has been used in this example and is given in Figure 6.12. In addition to entering the information from the problem statement into the spreadsheet (with any necessary conversion of units) a few additional calculations are needed, as described below.

### Estimating capital cost

The capital cost of the process can be estimated based on historic data using the correlation given in Table 6.2. The correlation is based on the plant capacity in MMlb/y, so we need to convert the capacity: 400 kt/y is equal to 880 MMlb/y:

$$\text{ISBL capital cost} = 3.533\ S^{0.6} = 3.533\,(880)^{0.6} = \$206.5\,\text{MM}$$

The ISBL cost is on a U.S. Gulf Coast basis, so we need to convert to a Northeast Asia basis. If we look up the location factor in Table 6.7, then it is not clear what factor we should use. The location factor for Japan is 1.26, while for China it varies from 0.6 to 1.1, depending on the amount of indigenous vs. imported equipment used. Since the exact location of the plant has not yet been specified, we are not able to make a definitive assessment of what the location factor should be. As a first approximation we therefore assume it is 1.0 and note that this should be revisited as part of the sensitivity analysis.

The OSBL capital cost is estimated as 40% of ISBL cost. The engineering cost and contingency are estimated as 10% and 15% of the sum (ISBL + OSBL) cost respectively, giving a total fixed capital cost of $361.3 MM.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Company Name** | Project Name | | Adipic acid from phenol | | | | | |
| Address | Project Number | | | | | | Sheet | 1 |
| **COST OF PRODUCTION** | REV | DATE | BY | APVD | REV | DATE | BY | APVD |
| **Adipic Acid from Phenol** | 1 | 1.1.07 | GPT | | | | | |
| Form XXXXX-YY-ZZ | | | | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| Owner's Name | | Capital Cost Basis Year | 2006 | | |
| Plant Location | Northeast Asia | Units | Metric | | |
| Case Description | | On Stream | 8,000 | hr/yr | 333.33 day/yr |

**YIELD ESTIMATE**

Yield information taken from ChemSystems PERP report 98/99-3, Adipic Acid, p. 89
Yields input for phenol, nitric acid, hydrogen, off-gas, utilities and consumables

Scale of production set to 400 t/y = 880 MMlb/yr

**CAPITAL COSTS**

| | $MM |
|---|---|
| ISBL Capital Cost | 206.5 |
| OSBL Capital Cost | 82.6 |
| Engineering Costs | 28.9 |
| Contingency | 43.4 |
| Total Fixed Capital Cost | 361.3 |
| Working Capital | 59.5 |

**REVENUES AND RAW MATERIAL COSTS**

MASS BALANCE MB closure 101%

| Key Products | Units | Units/Unit product | Units/yr | Price $/unit | $MM/yr | $/unit main product |
|---|---|---|---|---|---|---|
| Adipic acid | t | 1 | 400,000 | 1400 | 560.00 | 1400.00 |
| Total Key Product Revenues (REV) | t | 1 | 400,000 | | 560.00 | 1400.00 |
| **By-products & Waste Streams** | | | | | | |
| Nitrous oxide (vented) | t | | 100,261 | 0 | 0.00 | 0.00 |
| Off-gas | t | 0.00417 | 1,670 | 700 | 1.17 | 2.92 |
| Organic Waste (Fuel value) | t | 0.03072 | 12,288 | 300 | 3.69 | 9.22 |
| Aqueous Waste | t | | 273,440 | -1.5 | -0.41 | -1.03 |
| Total Byproducts and Wastes (BP) | t | 0.0348939 | 387,659 | | 4.44 | 11.11 |
| **Raw Materials** | | | | | | |
| Phenol | t | 0.71572 | 286,288 | 1000 | 286.29 | 715.72 |
| Nitric acid 60% (100% basis) | t | 0.71778 | 287,112 | 380 | 109.10 | 272.76 |
| water with nitric acid | t | | 191,408 | 0 | 0.00 | 0.00 |
| Hydrogen, 99% | t | 0.0351 | 14,040 | 1100 | 15.44 | 38.61 |
| Total Raw Materials (RM) | | 1 | 778,848 | | 410.83 | 1027.09 |
| Gross Margin (GM = REV + BP - RM) | | | | | 153.61 | 384.03 |

**CONSUMABLES**

| | Units | Units/Unit product | Units/yr | Price $/unit | $MM/yr | $/unit product |
|---|---|---|---|---|---|---|
| Various catalyst and chemicals | kg | 32.85 | 13,138,263 | 1.00 | 13.14 | 32.85 |
| Other | kg | 0 | 0 | 0.00 | 0.00 | 0.00 |
| Total Consumables (CONS) | | | | | 13.14 | 32.85 |

**UTILITIES**

| | Units | Units/Unit product | Units/hr | Price $/unit | $MM/yr | $/unit product |
|---|---|---|---|---|---|---|
| Electric | kWh | 206.0 | 10,300 | 0.05 | 4.120 | 10.30 |
| HP Steam | t | 0.4 | 18 | 14.30 | 2.002 | 5.01 |
| MP Steam | t | 7.6 | 382 | 12.00 | 36.624 | 91.56 |
| LP Steam | t | 0.0 | 0 | 8.90 | 0.000 | 0.00 |
| Boiler Feed | t | 0.3 | 17 | 1.10 | 0.145 | 0.36 |
| Condensate | t | 0.0 | 0 | 0.80 | 0.000 | 0.00 |
| Cooling Water | t | 463.0 | 23,150 | 0.024 | 4.445 | 11.11 |
| Fuel Fired | GJ | 0.0 | 0 | 6.00 | 0.000 | 0.00 |
| Total Utilities (UTS) | | | | | 47.336 | 118.340 |
| Variable Cost of Production (VCOP = RM - BP + CONS + UTS) | | | | | 466.86 | 1167.16 |

**FIXED OPERATING COSTS**

| | | | $MM/yr | $/unit product |
|---|---|---|---|---|
| Labor | | | | |
| | 4.8 | Operators per Shift Position | | |
| Number of shift positions | 9 | 30,000 $/yr each | 1.30 | 3.24 |
| Supervision | | 25% of Operating Labor | 0.32 | 0.81 |
| Direct Ovhd. | | 45% of Labor & Superv. | 0.73 | 1.82 |
| Maintenance | | 3% of ISBL Investment | 10.84 | 27.10 |
| Overhead Expense | | | | |
| Plant Overhead | | 65% of Labor & Maint. | 8.57 | 21.43 |
| Tax & Insurance | | 2% of Fixed Investment | 5.42 | 13.55 |
| Interest on Debt Financing | | 0% of Fixed Capital | 0.00 | 0.00 |
| | | 6% of Working Capital | 3.57 | 8.93 |
| | | Fixed Cost of Production (FCOP) | 30.75 | 76.88 |

**ANNUALIZED CAPITAL CHARGES**

| | $MM | Interest Rate | Life (yr) | ACCR | $MM/yr | $/unit product |
|---|---|---|---|---|---|---|
| Fixed Capital Investment | 361.303 | 15% | 10 | 0.199 | 71.99 | 179.98 |
| Royalty Amortization | 15.000 | 15% | 10 | 0.199 | 2.99 | 7.47 |
| Inventory Amortization | | | | | | |
| Catalyst 1 | 0.000 | 15% | 3 | 0.438 | 0.00 | 0.00 |
| Catalyst 2 | 0.000 | 15% | 3 | 0.438 | 0.00 | 0.00 |
| Adsorbent 1 | 0.000 | 15% | 3 | 0.438 | 0.00 | 0.00 |
| Equipment 1 | 0.000 | 15% | 5 | 0.298 | 0.00 | 0.00 |
| Equipment 2 | 0.000 | 15% | 5 | 0.298 | 0.00 | 0.00 |
| Total Annual Capital Charge | | | | | 74.98 | 187.45 |

**SUMMARY**

| | $MM/yr | $/unit product |
|---|---|---|
| Variable Cost of Production | 466.86 | 1167.16 |
| Fixed Cost of Production | 30.75 | 76.88 |
| Cash Cost of Production | 497.61 | 1244.04 |
| Gross Profit | 62.39 | 155.96 |
| Total Cost of Production | 572.59 | 1431.48 |

**FIGURE 6.12**

Cost of production worksheet for Example 6.11.

### *Closing mass balance*

The first thing that is apparent when entering the yield data is that the mass balance for the process does not close properly with the information given. This suggests that we still need to account for some waste streams.

The first waste stream is apparent from the process stoichiometry. Nitric acid is recycled in the process until it is eventually converted to $N_2O$ and vented to the atmosphere. The yield of $N_2O$ can therefore be found by a mass balance on nitrogen:

$$\text{Nitrogen fed} = \text{nitrogen purged}$$

$$400{,}000 \times 0.71778 \times \frac{14}{63} = m_{N2O} \times \frac{2 \times 14}{44}$$

where $m_{N2O}$ is the flow rate of $N_2O$, which can be calculated as 100,261 MT/y. As a first approximation, there is no cost for handling this stream, although we might revisit this at a more detailed design stage if we need to fit vent scrubbers or other equipment to handle this off-gas.

The second waste stream is also apparent from the overall stoichiometry. Phenol has a molecular weight of 100 and adipic acid has a molecular weight of 146, so the stoichiometric requirement of phenol is = 100/146 = 0.68493 lb/lb product. The actual process consumption has been estimated as 0.71572 lb/lb product, so the difference (0.71572 – 0.68493 = 0.03079 lb/lb) must be converted into organic by-products. It is possible that some of the organic by-product may be material that is lost with the hydrogen-rich fuel gas, but as a first approximation we can assume that we recover an organic liquid waste product from the process. It is also possible (in fact quite likely) that some of the material that we are calling organic by-product is actually losses of organics in the nitrous oxide vent stream. Since this stream probably must be scrubbed before discharge, it is fair to assume as a first approximation that any organic material in it would be collected as an organic waste. This assumption should be revisited at a later stage in the design process when better information on process yields is available. The organic waste stream is priced at a typical fuel value of $300/t, assuming that it can be burned as process fuel.

The third waste stream is an aqueous waste. This consists of the water that is brought in with the nitric acid, the water formed by the reaction stoichiometry and any other water consumed, for example in vent scrubbers or process water washes.

The water brought in with the nitric acid is easily found by mass balance, since it is equal to the mass flow rate of nitric acid (100% basis) × 40/60 = 400,000 × 0.71778 × 4/6 = 191,408 t/y.

The water formed by reaction stoichiometry can be estimated as 1 mole per mole nitric acid consumed, i.e. 18 t per 63 t consumed, giving 400,000 × 0.71778 × 18/63 = 82,032 t/y. Note that we could also have estimated this as 2 moles per mole product, but that would give an overestimate of the water production as the amount of nitric acid consumed is less than the apparent stoichiometric requirement. This is because the overall reaction given above is only an approximation and does not include the reaction of cyclohexanone.

The water consumed in process washes and scrubbers is harder to estimate, but since no process water consumption was listed under utilities, we can assume as a first approximation that all the process water needs are met by internal recycles. This gives a total waste water flow of 191,408 + 82,032 = 273,440 t/y. The waste water stream is assigned a cost of $1.5/t (see Section 6.4.6)

When the values above for nitrous oxide, organic waste and aqueous waste are entered in the spreadsheet, the mass balance shows 101 t of product for every 100 t of feed. This is not perfectly closed, but is good enough at this stage in the analysis. The error is most likely in the organic or aqueous waste streams and will have little impact on the economic analysis. This should of course be revisited when better process yield data and a converged process simulation are available.

### *Estimating utility costs*

The amounts of utilities consumed are easily estimated from the production rate and the information in the problem statement (with conversion to metric units).

The prices of steam at different levels can be taken from Example 6.6, since the costs of fuel and natural gas are the same.

The prices of boiler feed water, condensate and cooling water are estimated as described in Section 6.4.4.

The utility cost is about 10% of the variable cost of production. This is typical for many commodity chemical processes.

*Estimating fixed costs*

The adipic acid process is a relatively complex process and essentially contains two plants – phenol hydrogenation and KA oil oxidation. We should therefore assume at least 4 shift positions for each plant, say 9 total. For a Northeast Asia basis we expect that the salary cost per shift position will be lower than the typical $50,000 per year that we would assume for a U.S. Gulf Coast plant. As a first approximation this is estimated as $30,000/y. The remaining salary and overhead costs are fixed following the assumptions given in Section 6.2.4.

Interest charges are not included for the fixed capital (since we will calculate an annualized charge based on overall cost of capital below). An interest charge is included for the working capital, as working capital is recovered at the end of the project and so should not be amortized, as discussed in Section 6.7.6.

The total fixed cost of production is calculated to be $31 MM/y, which is low, compared to the variable cost of production ($467 MM/y). It is not uncommon for fixed costs to make a relatively minor contribution to the total cost of production for a world-scale plant.

*Estimating working capital*

The working capital is estimated as seven weeks' cash cost of production minus two weeks' feedstock costs plus 1% of the fixed capital investment, as described in Section 6.2.2. Because the cash cost of production includes the interest payable on the working capital, this sets up a circular reference in the spreadsheet. The spreadsheet options must be adjusted to ensure that the calculation iterates to convergence. The converged result is $59.5 MM. Note that the value calculated is about 10% greater than it would have been had we estimated the working capital as 15% of fixed capital investment.

*Estimating annualized capital costs*

The fixed capital investment is to be annualized over 10 years at a 15% interest rate. For this interest rate and recovery period the annual capital charge ratio is 0.199, so the annual capital charge is = 0.199 × 361.3 = $71.99 MM/y, or $179.98 /t of product. As a quick check, we can see that this is roughly 10% of the total cost of production, which is typical for commodity chemical processes.

In addition to the fixed capital investment, we should also make an allowance for a process royalty. The problem statement did not specify whether the plant was to be built using proprietary technology, but it is reasonable to assume that a royalty will need to be paid. If a $15 MM royalty is added then this annualizes to a cost of $3 MM/y, or roughly 0.5% of revenues, which is a reasonable initial estimate. This should be revisited during more detailed design when discussions with technology vendors take place.

*Estimating cost of production*

The cash cost of production is the sum of the fixed and variable production costs (equation 6.2):

$$\text{CCOP} = \text{VCOP} + \text{FCOP} = 466.86 + 30.75 = \$497.61\ \text{MM/y}$$

The total cost of production is the sum of the cash cost of production and the annual capital charge (equation 6.5):

$$\text{TCOP} = \text{CCOP} + \text{ACC} = 497.61 + 74.98 = \$572.59\ \text{MM/y}$$

It is worth noting that the calculated total cost of production is greater than the projected annual revenue of $560 MM/y. This suggests that the project would not earn the expected 15% interest rate. This is explored further in the following example and in problems 6.14 and 6.15.

## EXAMPLE 6.12

The adipic acid plant in Example 6.11 is built with 30% of the fixed investment in year 1 and 70% in year 2, and the plant operates at 50% of capacity in year 3 before reaching full capacity in year 4. The plant can be depreciated by the straight-line method over ten years and profits can be assumed to be taxed at 35% per year, payable the next year. Assume that losses cannot be offset against revenues from other operations for tax purposes (i.e., no tax credits in years when the plant makes a loss). Estimate the following:

1. The cash flow in each year of the project.
2. The simple pay-back period.
3. The net present value with a 15% cost of capital for 10 years and 15 years of production at full capacity.
4. The DCFROR for 15 years of production at full capacity.

   Is this an attractive investment?

## Solution

The solution requires calculating the cash flows in each year of the project. This is easily coded into a spreadsheet, as illustrated in Figure 6.13. A blank template of this spreadsheet is given in Appendix G and is available in MS Excel format in the on-line material at http://books.elsevier.com/companions.

**Company Name**
Address

**ECONOMIC ANALYSIS**
**Adipic Acid from Phenol**

Form XXXXX-YY-ZZ

Project Name: Adipic acid from phenol
Project Number
Sheet 1

| REV | DATE | BY | APVD | REV | DATE | BY | APVD |
|---|---|---|---|---|---|---|---|
| 1 | 1.1.07 | GPT | | | | | |

| | | | |
|---|---|---|---|
| Owner's Name | | Capital Cost Basis Year | 2006 |
| Plant Location | Northeast Asia | Units | Metric |
| Case Description | | On Stream | 8,000 hr/yr 333.33 day/yr |

REVENUES AND PRODUCTION COSTS

| | $MM/yr |
|---|---|
| Main product revenue | 560.0 |
| Byproduct revenue | 4.4 |
| Raw materials cost | 410.8 |
| Utilities cost | 47.3 |
| Consumables cost | 13.1 |
| VCOP | 466.8 |
| Salary and overheads | 16.4 |
| Maintenance | 10.8 |
| Interest | 3.6 |
| Royalties | 3.0 |
| FCOP | 33.8 |

CAPITAL COSTS

| | $MM |
|---|---|
| ISBL Capital Cost | 206.5 |
| OSBL Capital Cost | 82.6 |
| Engineering Costs | 28.9 |
| Contingency | 43.4 |
| Total Fixed Capital Cost | 361.3 |
| Working Capital | 59.5 |

CONSTRUCTION SCHEDULE

| Year | % FC | % WC | % FCOP | % VCOP |
|---|---|---|---|---|
| 1 | 30% | 0% | 0% | 0% |
| 2 | 70% | 0% | 0% | 0% |
| 3 | 0% | 100% | 100% | 50% |
| 4 | 0% | 0% | 100% | 100% |
| 5 | 0% | 0% | 100% | 100% |
| 6 | 0% | 0% | 100% | 100% |
| 7+ | 0% | 0% | 100% | 100% |

ECONOMIC ASSUMPTIONS

| | | | | | |
|---|---|---|---|---|---|
| Cost of equity | 25% | Debt ratio | 0.5 | Tax rate | 35% |
| Cost of debt | 5% | | | Depreciation method | Straight-line |
| Cost of capital | 15.0% | | | Depreciation period | 10 years |

CASH FLOW ANALYSIS

All figures in $MM unless indicated

| Project year | Cap Ex | Revenue | CCOP | Gr. Profit | Deprcn | Taxbl Inc | Tax Paid | Cash Flow | PV of CF | NPV |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 108.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | -108.4 | -94.3 | -94.3 |
| 2 | 252.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | -252.9 | -191.2 | -285.5 |
| 3 | 59.5 | 280.0 | 267.2 | 12.8 | 36.1 | -23.3 | 0.0 | -46.7 | -30.7 | -316.2 |
| 4 | 0.0 | 560.0 | 500.6 | 59.4 | 36.1 | 23.3 | 0.0 | 59.4 | 34.0 | -282.2 |
| 5 | 0.0 | 560.0 | 500.6 | 59.4 | 36.1 | 23.3 | 8.1 | 51.3 | 25.5 | -256.8 |
| 6 | 0.0 | 560.0 | 500.6 | 59.4 | 36.1 | 23.3 | 8.1 | 51.3 | 22.2 | -234.6 |
| 7 | 0.0 | 560.0 | 500.6 | 59.4 | 36.1 | 23.3 | 8.1 | 51.3 | 19.3 | -215.3 |
| 8 | 0.0 | 560.0 | 500.6 | 59.4 | 36.1 | 23.3 | 8.1 | 51.3 | 16.8 | -198.6 |
| 9 | 0.0 | 560.0 | 500.6 | 59.4 | 36.1 | 23.3 | 8.1 | 51.3 | 14.6 | -184.0 |
| 10 | 0.0 | 560.0 | 500.6 | 59.4 | 36.1 | 23.3 | 8.1 | 51.3 | 12.7 | -171.3 |
| 11 | 0.0 | 560.0 | 500.6 | 59.4 | 36.1 | 23.3 | 8.1 | 51.3 | 11.0 | -160.3 |
| 12 | 0.0 | 560.0 | 500.6 | 59.4 | 36.1 | 23.3 | 8.1 | 51.3 | 9.6 | -150.7 |
| 13 | 0.0 | 560.0 | 500.6 | 59.4 | 0.0 | 59.4 | 8.1 | 51.3 | 8.3 | -142.4 |
| 14 | 0.0 | 560.0 | 500.6 | 59.4 | 0.0 | 59.4 | 20.8 | 38.6 | 5.5 | -136.9 |
| 15 | 0.0 | 560.0 | 500.6 | 59.4 | 0.0 | 59.4 | 20.8 | 38.6 | 4.7 | -132.2 |
| 16 | 0.0 | 560.0 | 500.6 | 59.4 | 0.0 | 59.4 | 20.8 | 38.6 | 4.1 | -128.1 |
| 17 | 0.0 | 560.0 | 500.6 | 59.4 | 0.0 | 59.4 | 20.8 | 38.6 | 3.6 | -124.5 |
| 18 | 0.0 | 560.0 | 500.6 | 59.4 | 0.0 | 59.4 | 20.8 | 38.6 | 3.1 | -121.4 |
| 19 | 0.0 | 560.0 | 500.6 | 59.4 | 0.0 | 59.4 | 20.8 | 38.6 | 2.7 | -118.7 |
| 20 | -59.5 | 560.0 | 500.6 | 59.4 | 0.0 | 59.4 | 20.8 | 98.1 | 6.0 | -112.7 |

ECONOMIC ANALYSIS

| | | | | | | |
|---|---|---|---|---|---|---|
| Average cash flow | 44.7 $MM/yr | NPV | 10 years | -171.3 $MM | IRR 10 years | -2.0% |
| Simple pay-back period | 9.4 yrs | | 15 years | -132.2 $MM | 15 years | 5.6% |
| Return on investment (10 yrs) | 3.32% | | 20 years | -112.7 $MM | 20 years | 8.4% |
| Return on investment (15 yrs) | 5.77% | NPV to yr | 19 | -118.7 $MM | | |

**FIGURE 6.13**

Economic analysis worksheet for Example 6.12.

### Cash flow table

In years 1 and 2 of the project there are capital expenses but no revenues or operating costs. The capital expenses are not operating losses and so they have no effect on taxes or depreciation. They are negative cash flows.

In year 3 the plant operates at 50% capacity and generates 50% of the design basis revenue. All of the working capital must be invested. The plant incurs 100% of the fixed cost of production but only 50% of the variable cost. Because the plant makes a profit, depreciation can be charged. Using the straight-line method of depreciation with a ten year recovery period, the annual depreciation charge is one-tenth of the total fixed capital investment = 361.3/10 = $36.1 MM. Since the gross profit in year 3 is only $12.8 MM, the effect of charging depreciation is that the taxable income is negative and so no taxes are owed in year 4 (taxes are paid based on the previous year's income).

In year 4 the plant operates at full capacity and generates 100% of the design basis revenues with 100% of the VCOP. From here onwards the plant makes a gross profit of $59.4 MM each year.

Depreciation is charged for ten years, i.e., until year 12. The taxable income therefore increases in year 13 and the taxes paid increase in year 14, giving a reduction in cash flow from $51.3 MM to $38.6MM.

In the final year of the project, the working capital is released and should be taken as a positive increment to the cash flow. This is shown as occurring in year 20 in Figure 6.13, but should be adjusted when the length of the project is varied, as described below.

The present value of the cash flow in year $n$ can be found by multiplying by $(1 + i)^{-n}$, as described in equation 6.40. The net present value up to year $n$ is the cumulative sum of all the present values of cash flow up to that year.

### Simple pay-back period

The simple pay-back is calculated from the fixed investment and the average annual cash flow (equation 6.36). The average annual cash flow should be based only on the years in which the plant generates revenue, i.e., years 3 to 20, and is found to be $44.7 MM/y. Note that it does not matter if this range includes the year in which working capital is invested, as long as it also includes the year in which working capital is recovered. The working capital thereby cancels out and is not included in the average cash flow.

The simple pay-back period is then found from:

$$\text{simple pay-back time} = \frac{\text{total investment}}{\text{average annual cash flow}} = \frac{361.3}{44.7} = \underline{\underline{8.08 \text{ years}}} \tag{6.36}$$

### Net present value

The net present value with a 15% cost of capital after 10 years of production is the NPV at the end of year 13. This can be looked up in the cash flow table and is $-142.4 MM. If the plant is closed after 10 years of production and the working capital is released, then there would be an additional cash flow of $59.1 MM in year 13, increasing the NPV to $-132.7 MM.

The net present value after 15 years of production is the NPV at the end of year 18, which can also be found from the cash flow table and is $-121.4 MM. If the plant is closed after 15 years of production and the working capital is released, then there would be an additional cash flow of $59.1 MM in year 18, increasing the NPV to $-116.6 MM.

In all cases the NPV for this project is negative, so it is not an attractive investment with a 15% cost of capital. We already knew this would be the case based on the cost of production analysis in Example 6.11, which had shown that the TCOP with capital recovered at a 15% interest rate was greater than the expected revenue.

### Internal rate of return (DCFROR)

The DCFROR (IRR) of the project after 15 years of production at full capacity can be found by either adjusting the interest rate (manually or using the goal seek function) until the NPV at the end of year 18 is equal to zero, or by using the IRR function in the spreadsheet over the range year 1 to year 18. The working capital should be included as a recovered cost in year 18.

The answer obtained in either case is DCFROR = 7.85%. This is the maximum interest rate at which this project can be financed to break even in 15 years of production.

### Summary

None of the economic measures indicates that this is an attractive project with the projected costs, revenues and capital expenses. It should perhaps be noted though, that this analysis was based on a class 5 estimate of the capital cost (± 50%). If we had any technical improvement in mind that could reduce either the capital investment or the cost of production, then we might want to develop the design further to assess if the economic analysis was sufficiently improved.

### EXAMPLE 6.13

A plant is producing 10,000 metric tons per year (10 kMTA) of a product. The overall yield is 70 per cent, on a mass basis (kg of product per kg raw material). The raw material costs \$500/metric ton, and the product sells for \$900/metric ton. A process modification has been devised that will increase the yield to 75 per cent. The additional investment required is \$1,250,000, and the additional operating costs are negligible. Is the modification worth making?

**Solution**

There are two ways of looking at the earnings to be gained from the modification:

1. If the additional production given by the yield increase can be sold at the current price, the earnings on each additional ton of production will equal the sales price less the raw material cost.
2. If the additional production cannot be readily sold, the modification results in a reduction in raw material requirements, rather than increased sales, and the earnings (savings) are from the reduction in annual raw material costs.

The second way gives the lowest figures and is the safest basis for making the evaluation. At 10 kMTA production:

Raw material requirements at 70% yield $= \frac{10,000}{0.7} = 14,286$

$$\text{at 75 \%yield} = \frac{10,000}{0.75} = 13,333$$

Cost savings = 953 metric tons/year, which is worth 953 × 500 = \$476,500/year

$$\text{Pre-tax ROI} = \frac{476,500}{1,250,000} = \underline{\underline{38\%}}$$

As the annual savings are constant, the simple pay-back period is the inverse of the pre-tax ROI:

$$\text{Simple pay-back period} = \frac{1,250,000}{476,500} = \underline{\underline{2.62 \text{ years}}}$$

Based on the attractive ROI and pay-back period, this investment would seem to be worth pursuing further. Whether or not it was implemented would depend on the hurdle rate set for investments by the company.

## 6.8 SENSITIVITY ANALYSIS

### 6.8.1 SIMPLE SENSITIVITY ANALYSIS

The economic analysis of a project can only be based on the best estimates that can be made of the investment required and the cash flows. The actual cash flows achieved in any year will be affected by changes in raw materials costs and other operating costs; and will be very dependent on the sales volume and price. A sensitivity analysis is a way of examining the effects of uncertainties in the forecasts on the viability of a project. To carry out the analysis, the investment and cash flows are first calculated using what are considered the most probable values for the various factors; this establishes the base case for analysis. Various parameters in the cost model are then adjusted, assuming a range of error for each factor in turn. This will show how sensitive the cash flows and economic criteria are to errors in the forecast figures. A sensitivity analysis gives some idea of the degree of risk involved in making judgments on the forecast performance of the project.

The results of a sensitivity analysis are usually presented as plots of an economic criterion such as NPV or DCFROR vs. the parameter studied. Several plots are sometimes shown on the same graph using a scale from 0.5 × base value to 2 × base value as the abscissa.

### 6.8.2 PARAMETERS TO STUDY

The purpose of sensitivity analysis is to identify those parameters that have a significant impact on project viability over the expected range of variation of the parameter. Typical parameters investigated and the range of variation that is usually assumed are given in Table 6.12.

Varying the production rate (while keeping investment and fixed costs constant) investigates the effects of unexpectedly high down time due to maintenance or operations problems, as well as unexpected difficulties in selling the full volume of product that could be produced. An increase in production rate beyond the design capacity might also be possible if the plant design margins allow some extra capacity or if the yields can be improved by use of a better catalyst, etc.

The choice of which feed and product prices to use in the sensitivity analysis depends on the method of price forecasting that has been used. Typically, total raw material cost is studied rather than treating each feed separately, but if raw material costs are found to be the dominant factor then they may be broken out into the costs of individual raw materials.

### 6.8.3 STATISTICAL METHODS FOR RISK ANALYSIS

In a simple sensitivity analysis, each parameter is varied individually and the output is a qualitative understanding of which parameters have the most impact on project viability. In a more formal risk analysis, statistical methods are used to examine the effect of variation in all of the parameters simultaneously and hence quantitatively determine the range of variability in the economic criteria.

**Table 6.12 Sensitivity analysis parameters**

| Parameter | Range of variation |
|---|---|
| Sales price | ± 20% of base (larger for cyclic commodities) |
| Production rate | ± 20% of base |
| Feed cost | − 10% to + 30% of base |
| Fuel cost | − 50% to + 100% of base |
| Fixed costs | − 20% to + 100% of base |
| ISBL capital investment | − 20% to + 50% of base |
| OSBL capital investment | − 20% to + 50% of base |
| Construction time | − 6 months to + 2 years |
| Interest rate | base to base + 2 percentage points |

This allows the design engineer to estimate the degree of confidence with which the chosen economic criterion can be said to exceed a given threshold.

A simple method of statistical analysis was proposed by Piekarski (1984) and is described in Humphreys (2005). Each item in the estimate is expressed as a most likely value, $ML$, an upper value, $H$, and a lower value, $L$. The upper and lower values can be estimated using the ranges of variation given in Table 6.12. The mean and standard deviation are then estimated as:

$$\text{mean value,}\quad \bar{x} = \frac{(H + 2ML + L)}{4} \tag{6.51}$$

$$\text{standard deviation,}\quad S_x = \frac{(H - L)}{2.65} \tag{6.52}$$

Note that the mean is not necessarily equal to the most likely value if the distribution is skewed. This is often the case for cost functions.

The mean and standard deviation of other parameters can then be estimated by combination of the individual means and standard deviations using the mathematics of statistics given in Table 6.13.

This allows relatively easy estimation of the overall error in a completed cost estimate, and with a little more difficulty can be extended to economic criteria such as NPV, TAC or ROI.

Rather than build the simple method above into a spreadsheet, a more sophisticated approach is to take the economic model and subject it to analysis using Monte Carlo simulation. In Monte Carlo simulation, random numbers are generated and used to establish the value of each parameter within its allowed range. For example, each parameter could be set equal to $L + (R \times (H - L)/10)$, where $R$ is a random number between 0 and 10. The overall probability distribution in the calculated parameter (economic criterion) can be estimated by performing a large number of such simulations. Several commercial programs for Monte Carlo simulation are available, for example REP/PC (Decision Sciences Corp.), @RISK (Palisade Corp.) and CRYSTAL BALL® (Decisioneering® Corp.).

**Table 6.13 Mathematics of statistics**
**If: $y = f(\bar{x}, \bar{z})$, then the standard deviation of $y$, $S_y$ is given as a function of $S_x$ and $S_z$.**

| Function $y$ of $\bar{x}$, $\bar{z}$ | Standard deviation $S_y$ |
|---|---|
| $y = a\bar{x} + b\bar{z}$ | $S_y = \sqrt{a^2 S_x^2 + b^2 S_z^2}$ |
| $y = \bar{x}\,\bar{z}$ | $S_y = \bar{x}\bar{z}\sqrt{\frac{S_x^2}{\bar{x}^2} + \frac{S_z^2}{\bar{z}^2}}$ |
| $y = \frac{\bar{x}}{\bar{z}}$ | $S_y = \frac{\bar{x}}{\bar{z}}\sqrt{\frac{S_x^2}{\bar{x}^2} + \frac{S_z^2}{\bar{z}^2}}$ |

*Note:*
1. *These formulae are strictly true only when the covariance of x and z is zero, i.e., there is no statistical interrelation between x and z, and when x and z have been estimated from a small set of data points.*
2. *For a more general description of the formulae, see Ku (1966).*

Care must be taken in formulating Monte Carlo simulation problems. The Monte Carlo method implicitly assumes that all parameters vary randomly and independently. If two parameters are correlated (for example feedstock and product prices or feedstock and energy prices) then they should not be varied independently. The correct approach is to vary one of the parameters and then predict the other by correlation, imposing a random error on the predicted parameter to reflect the accuracy of the correlation.

The cost estimating literature contains a lot of information on risk analysis. Good introductions to the use of statistics in risk analysis are given by Humphreys (2005) and Sweeting (1997).

### 6.8.4 CONTINGENCY COSTS

The concept of a contingency charge to allow for variation in the capital cost estimate was introduced in Section 6.2.1, where it was suggested that a minimum contingency charge of 10% of ISBL plus OSBL fixed capital should be used.

If the confidence interval of the estimate is known, then the contingency charges can also be estimated based on the desired level of certainty that the project will not overrun the projected cost. For example, if the cost estimate is normally distributed then the estimator has the following confidence levels:

- 90% confidence that the cost is less than $\bar{x} + 1.3\ S_x$.
- 95% confidence that the cost is less than $\bar{x} + 1.65\ S_x$.
- 98% confidence that the cost is less than $\bar{x} + 2.05\ S_x$.
- 99% confidence that the cost is less than $\bar{x} + 2.33\ S_x$.

Although many of the components of a cost estimate are skewed distributions, when these are combined the resulting distribution is often approximately normal. The above guidelines can thus be used to determine the amount of contingency charge needed for a given level of confidence.

Note also that a 10% contingency charge gives 98% confidence of the cost coming in under estimate if the estimate has accuracy $\pm$ 6.5% (using the approximate method of calculating $S_x$ given in equation 6.52). This illustrates that a 10% contingency charge should really be viewed as a minimum level and is only appropriate for detailed estimates (Class 1 and Class 2), when the technology is well understood. Additional guidance on improving estimates of contingency costs is given by Hollman (2014).

#### EXAMPLE 6.14

A preliminary (Class 4) estimate of the ISBL capital cost of building a 200,000 ton per year ethanol plant by corn dry milling has been stated as \$130 MM -30% / +50%. The plant is to be built on a green-field site and offsite costs are estimated to be between \$40 MM and \$60 MM. Estimate a value for the total project cost that will give 98% confidence that the project can be carried out within the amount estimated.

**Solution**

For the ISBL cost, H = \$195 MM, L = \$91 MM and ML = \$130 MM, so:

$$\bar{x}_{ISBL} = \frac{(H + 2ML + L)}{4} = \frac{(195 + 260 + 91)}{4} = \$136.5\ \text{MM} \tag{6.51}$$

$$S_{x,ISBL} = \frac{(H - L)}{2.65} = \frac{195 - 91}{2.65} = \$39.2 \text{ MM} \quad (6.52)$$

Similarly, for the OSBL costs, assuming the most likely value is in the middle of the range given:

$$\bar{x}_{OSBL} = \frac{(H + 2ML + L)}{4} = \frac{(40 + 100 + 60)}{4} = \$50 \text{ MM} \quad (6.51)$$

$$S_{x,OSBL} = \frac{(H - L)}{2.65} = \frac{60 - 40}{2.65} = \$7.55 \text{ MM} \quad (6.52)$$

Both mean values should be increased by 10% to allow for Engineering costs, so combining the means gives:

$$\bar{x}_{Total} = 1.1\bar{x}_{ISBL} + 1.1\bar{x}_{OSBL} = \$205.2 \text{ MM}$$

$$S_{x,Total} = \sqrt{(1.1S_{x,ISBL})^2 + (1.1S_{x,OSBL})^2} = \$43.9 \text{ MM}$$

We have 98% confidence that the cost is less than $\bar{x} + 2.05\, S_x = 205.2 + (2.05 \times 43.9) =$ $ 295 MM. If we budget the project for this amount (or tender a contract) then we are accepting a 1 in 50 risk that the project will exceed the given budget.

## 6.9 PROJECT PORTFOLIO SELECTION

A typical company involved in the chemical, pharmaceutical or fuels industries will evaluate many projects each year. Only a few of these projects are selected for implementation. This section discusses some of the criteria and methods used in making that selection.

### 6.9.1 TYPES OF PROJECTS

Investment projects are carried out for a variety of reasons.

*Regulatory compliance projects* are often required as a result of changes in environmental or other legislation. If the government changes the rules on plant safety, emissions or product specifications, then unless an exemption can be obtained the plant must be modified or closed down. Regulatory compliance projects often have poor financial performance unless the costs of going out of business are considered.

*Cost reduction projects* are aimed at reducing the cost of production of an existing plant. The most common cost reduction investments are for *preventive maintenance*, in which equipment is replaced, repaired or cleaned after a planned interval and before the equipment deteriorates to the point where it could impact process performance or safety. Most preventive maintenance projects are small and are handled through the plant maintenance budget, but some can be very large expensive projects requiring a major plant shutdown, for example, replacing the fired tubes in a main plant furnace. Another common type of cost reduction project is *Heat recovery* or *Heat integration projects*, in which the plant heat exchange network or utility system is upgraded to reduce energy costs.

Whenever possible, companies also seek to fund *Growth projects* that can be expected to give high returns on the capital invested. Growth projects include expansions of existing units, often referred to as *Debottlenecking* or *Revamp projects* as well as construction of entirely new plants in *Grassroots projects*.

In all cases except grassroots projects, a large amount of information about the existing plant, site and products is usually needed before the project can be designed. Much effort is usually spent on reconciling simulation or other models to the plant performance so as to be useful for designing the plant modifications. Grassroots projects are typically used as undergraduate design projects because they are self-contained and do not require model reconciliation; however, in industrial practice they make up less than 10% of all projects.

## 6.9.2 LIMITS ON THE PROJECT PORTFOLIO

The most obvious limit on the portfolio of projects that can be funded is the availability of capital, which is in turn limited by the financing arrangements of the company (see Section 6.6).

Capital spending is often set in proportion to sales, operating profit or total assets. Table 6.14 shows recent information on capital spending for some of the largest chemical companies in the world. It can be seen from Table 6.14 that most of the companies' capital spending was between 4% and 8% of sales and also between 4% and 6% of assets. On average, capital spending was 6.9% of sales and 5.3% of assets.

A second important constraint on the number of projects that can be carried out is the availability of critical resources. Companies with small engineering staffs will only be able to carry out a few projects at one time. Even if extensive use is made of Engineering Procurement and Construction (EPC) contractors, the owners will still need to provide some engineering support to each project. The availability of EPC contractors can also be an issue during times of peak industry construction. Projects that require extensive research and development work may be delayed because of constraints on the availability of researchers and pilot plant facilities.

Often the most important constraint is set by regulatory timelines. Regulatory compliance projects must be completed in time for the plant or product to comply with the new law. This may dictate a narrow window of typically less than five years, in which the project must be planned, designed and constructed, giving the company little choice on when the project must be begun.

Regulatory timelines are extremely important for pharmaceutical products. A new drug is protected by patent for twenty years from the date the patent is filed. Beyond that time, competitors are able to sell generic versions of the drug and the price usually falls significantly. Before a new drug can be marketed, both the product and the manufacturing process must be approved by the Food and Drug Administration. Pharmaceutical manufacturers thus seek to maximize the revenue that they can obtain from a drug between FDA approval and patent expiration. This requires making advance preparations during the approvals process so that the rate of production can be ramped up quickly when final approval is obtained. The portfolio of investment projects for a pharmaceutical company will be strongly influenced by the expected outcomes of the regulatory approval process for new products.

**Table 6.14 Capital spending of large chemical companies**

| Company | Chemicals Sales (MM$) | Chemicals Net Profit (MM$) | Chemicals Assets (MM$) | Capital Spending (MM$) | Capital/ Sales | Capital/ Net profit | Capital/ Assets |
|---|---|---|---|---|---|---|---|
| BASF | 60,653 | 6,395 | 70,490 | 6,801 | 0.112 | 1.063 | 0.096 |
| Dow | 48,158 | 5,629 | 79,511 | 3,804 | 0.079 | 0.676 | 0.048 |
| Sinopec | 42,815 | 3,106 | 21,743 | 1,333 | 0.031 | 0.429 | 0.061 |
| SABIC | 30,985 | 10,101 | 40,112 | - | - | - | - |
| Formosa Plastics | 27,141 | 2,620 | 41,714 | - | - | - | - |
| ExxonMobil Chemical | 26,058 | 5,917 | 30,053 | 1,945 | 0.075 | 0.329 | 0.065 |
| Lyondell Basell | 24,624 | 5,638 | - | 2,006 | 0.081 | 0.356 | - |
| Ineos | 23,530 | 4,780 | - | - | - | - | - |
| Mitsubishi Chemical | 23,358 | 1,954 | 28,598 | 1,536 | 0.066 | 0.786 | 0.054 |
| DuPont | 19,679 | 4,081 | 12,748 | 704 | 0.036 | 0.173 | 0.055 |
| Air Liquide | 19,554 | 1,914 | 44,721 | 2,408 | 0.123 | 1.258 | 0.054 |
| LG Chem | 18,111 | 1,718 | 17,671 | 345 | 0.019 | 0.201 | 0.020 |
| Toray Industries | 16,533 | 1,427 | 19,417 | 1,336 | 0.081 | 0.936 | 0.069 |
| Linde | 16,488 | 2,453 | - | 1,838 | 0.111 | 0.749 | - |
| Akzo Nobel | 15,719 | 1,663 | 17,932 | 702 | 0.045 | 0.422 | 0.039 |
| PPG Industries | 14,270 | 2,356 | 15,549 | 402 | 0.028 | 0.171 | 0.026 |
| Evonik Industries | 14,097 | 1,726 | 21,750 | 1,050 | 0.074 | 0.608 | 0.048 |
| Reliance | 13,769 | 1,934 | 16,462 | 3,211 | 0.233 | 1.660 | 0.195 |
| Braskem | 13,692 | 2,760 | 14,826 | 815 | 0.060 | 0.295 | 0.055 |
| Sumitomo Chemical | 13,396 | 831 | 16,105 | 961 | 0.072 | 1.156 | 0.060 |

*Notes:*
1. Source: Tullo (2017).
2. Numbers are based on 2016 financial data.
3. Numbers reflect reported chemicals operations and do not include other activities such as oil and gas operations.

## 6.9.3 DECISION CRITERIA

Different types of projects are often judged using different economic criteria.

At the plant or site scale, management may have been given a small discretionary capital budget that can be used for preventive maintenance and cost reduction projects (if it is not swallowed up by regulatory compliance projects). These projects are often ranked using simple measures such as pay-back, ROI or total annualized cost. For a project to be considered for funding, it must meet a minimum (or maximum) criterion, known as a “hurdle rate”. For example, a company may dictate that projects should not be funded unless the pay-back period is less than two years. Regulatory compliance projects are often evaluated based on minimum incremental total annual cost, since it is implicitly assumed that there will be no additional revenue. If there is additional revenue, for example, from sale of a by-product, then this can be offset against the costs. If the cost of compliance is excessive, then the alternative costs of closing down or selling the site will also be evaluated.

Small projects or modifications to ongoing projects are often evaluated based on an “incremental ROI” defined as:

$$\text{Incremental ROI} = \frac{\text{incremental profit}}{\text{incremental investment}} \times 100\% \tag{6.53}$$

A separate hurdle rate is set for incremental ROI to ensure that modifications to a large project pay out in their own right and do not get funded just because of the attractiveness (or size) of the base project. This helps to prevent creep of project expenses.

Major growth and expansion projects that require significant investment are usually evaluated at the corporate level. Most companies look at the internal rate of return (IRR or DCFROR), the fixed and working capital and the NPV with the interest rate set equal to the cost of capital. The selection of projects is constrained by the factors described in Section 6.9.2. The set of projects chosen may also be strongly influenced by strategic factors such as the desire to expand a particular business or product line, or a desire to expand the presence of the company in a region that is experiencing rapid economic growth, such as India or China.

Two means of simplifying the selection problem are usually used so that the company senior management is not faced with a list of thousands of potential projects. The first is to set internal hurdle rates based on simple measures such as IRR or pay-back so that unattractive projects are weeded out at an early stage of the evaluation process. The second method is to divide the available capital budget into categories (sometimes referred to as “buckets”) so as to balance the competing needs of different regions and businesses, growth areas vs. established products, etc. The various strategic business units or regional subsidiaries (depending on how the company is organized) each submit their proposed capital budgets and a ranked list of projects. Corporate senior management then makes strategic adjustments between the different categories, and determines where to draw the line in each list such that the overall portfolio is balanced in accordance with the strategic objectives that they have set for the company. In a large corporation, this process may be repeated at two or more levels of management, with the list of selected projects being passed up to a higher level for further review and approval before the capital is authorized.

The problem of portfolio selection is easily expressed numerically as a constrained optimization: maximize economic criterion subject to constraint on available capital. This is a form of the “knapsack problem”, which can be formulated as a mixed-integer linear program (MILP), as long as the project sizes are fixed. (If not, then it becomes a mixed-integer non-linear program). In practice, numerical methods are very rarely used for portfolio selection, as many of the strategic factors considered are difficult to quantify and relate to the economic objective function.

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## 6.11 NOMENCLATURE

| | | Dimensions in $MLTθ |
|---|---|---|
| $A$ | Annual amount invested in equations 6.43 to 6.47 | $ |
| ACC | Annual capital charge | $ |
| $ACCR$ | Annual capital charge ratio | — |
| $a$ | Constant in equation 6.7 or equation 6.15 | $ |
| $B_m$ | Book value in after $m$ years of depreciation | $ |
| $b$ | Constant in equation 6.15 | $ |
| $C$ | Capital cost | $ |
| $C_d$ | Depreciable value | $ |
| $C_e$ | Purchased equipment cost | $ |
| $C_{e,i,A}$ | Purchased cost of equipment $i$ in alloy | $ |
| $C_{e,i,CS}$ | Purchased cost of equipment $i$ in carbon steel | $ |
| $C_1$ | Capital cost of plant with capacity $S_1$ | $ |
| $C_2$ | Capital cost of plant with capacity $S_2$ | $ |
| CCOP | Cash cost of production | $\$M^{-1}$ or $\$T^{-1}$ |
| $CF$ | Cash flow | $ |
| $CF_n$ | Cash flow in year $n$ | $ |
| $COP$ | Coefficient of performance of a refrigeration cycle | — |

*Continued*

| | | Dimensions in $MLTθ |
|---|---|---|
| $D$ | Sum of tax allowances, depreciation | $ |
| $D_c$ | Diameter of distillation column | L |
| $D_i$ | Depreciation charge in year $i$ | — |
| $DR$ | Debt ratio (leverage) | — |
| $dH_b$ | Boiler heating rate | $L^{-2}T^{2}$ |
| $F$ | Installation (Lang) factor | — |
| FCOP | Fixed cost of production | $\$M^{-1}$ or $\$T^{-1}$ |
| $F_d$ | Fraction of book value depreciated each year in declining balance method | — |
| $f_c$ | Installation factor for civil engineering work | — |
| $f_{el}$ | Installation factor for electrical work | — |
| $f_{er}$ | Installation factor for equipment erection | — |
| $f_i$ | Installation factor for instrumentation and control | — |
| $f_l$ | Installation factor for lagging, insulation and paint | — |
| $f_m$ | Materials factor | — |
| $f_p$ | Installation factor for piping | — |
| $f_s$ | Installation factor for structures and buildings | — |
| $H$ | High value of range (equation 6.51) | $ |
| $I$ | Taxable income | $ |
| $i$ | Interest rate | — |
| $i'$ | Discounted cash flow rate of return (internal rate of return) | — |
| $i_c$ | Cost of capital | — |
| $i_d$ | Interest rate due on debt | — |
| $i_e$ | Cost of equity | — |
| $L$ | Low value of range (equation 6.51) | $ |
| $L_c$ | Vessel length | L |
| $LF_A$ | Location factor for location $A$ relative to U.S. Gulf Coast basis | — |
| $M$ | Total number of pieces of equipment | — |
| $ML$ | Most likely value of range (equation 6.51) | $ |
| $m$ | Number of years | T |
| $N$ | Number of significant processing steps (functional units) | — |
| NPV | Net present value | S |
| $n$ | Capital cost exponent in equations 6.6 and 6.15 | — |
| $n$ | Number of years | T |
| $P$ | Gross profit, or principle invested in equations 6.43 to 6.47 | $ |
| $P_{BFW}$ | Price of boiler feed water | $\$M^{-1}$ |
| $P_F$ | Price of fuel | $\$M^{-1}L^{-2}T^{2}$ |
| $P_{HPS}$ | Price of high pressure steam | $\$M^{-1}$ |
| $P_{WFV}$ | Value of waste as fuel | $\$M^{-1}$ |
| $Q$ | Plant capacity | $MT^{-1}$ |
| ROA | Return on assets | — |
| ROE | Return on equity | — |

| | | Dimensions in \$MLTθ |
|---|---|---|
| ROI | Return on investment | — |
| $S$ | Plant or equipment capacity | * |
| $S$ | Matured sum in equations 6.43 to 6.47 | \$ |
| $S_x$ | Standard deviation | \$ |
| $S_1$ | Capacity of plant 1 | * |
| $S_2$ | Capacity of plant 2 | * |
| $s$ | Reactor conversion | — |
| $T_1$ | Evaporator absolute temperature | θ |
| $T_2$ | Condenser absolute temperature | θ |
| TAC | Total annualized cost | \$ |
| TCOP | Total cost of production | $\$M^{-1}$ or $\$T^{-1}$ |
| $t$ | Time, project life in years | T |
| $t_r$ | Tax rate | — |
| $t_w$ | Vessel wall thickness | L |
| VCOP | Variable cost of production | $\$M^{-1}$ or $\$T^{-1}$ |
| $\bar{x}$ | Mean value | \$ |
| $\Delta H^\circ_C$ | Heat of combustion | $L^{-2}T^2$ |
| $\eta_B$ | Boiler efficiency | — |
| $\rho$ | Metal density | $ML^{-3}$ |

*Asterisk (*) indicates that the dimensions are dependent on the type of equipment or process.*

## 6.12 PROBLEMS

**6.1.** Estimate the capital cost of a plant that produces 80,000 metric tons per year of caprolactam.

**6.2.** The process used in the manufacture of aniline from nitrobenzene is described in Appendix F, design problem F.8. The process involves six significant stages:

Vaporization of the nitrobenzene
Hydrogenation of the nitrobenzene
Separation of the reactor products by condensation
Recovery of crude aniline by distillation
Purification of the crude nitrobenzene
Recovery of aniline from waste water streams
Estimate the capital cost of a plant to produce 20,000 metric tons per year.

**6.3.** A reactor vessel cost \$365,000 in June 1998; estimate the cost in January 2010.

**6.4.** The cost of a distillation column was €225,000 in early 1998; estimate the cost in January 2011.

**6.5.** Using the data on equipment costs given in this chapter or commercial cost estimating software, estimate the cost of the following equipment:

1. A shell and tube heat exchanger, heat transfer area 50 $m^2$, floating head type, carbon steel shell, stainless steel tubes, operating pressure 25 bar.
2. A kettle reboiler: heat transfer area 25 $m^2$, carbon steel shell and tubes, operating pressure 10 bar.
3. A horizontal, cylindrical, storage tank, 3 m diameter, 12 m long, used for liquid chlorine at 10 bar, material carbon steel.
4. A plate column: diameter 2 m height 25 m, stainless clad vessel, 20 stainless steel sieve plates, operating pressure 5 bar.

**6.6.** Compare the cost the following types of heat exchangers, each with a heat transfer area of 10 $m^2$. Take the construction material as carbon steel.

1. Shell and tube, fixed head.
2. Double-pipe.

**6.7.** Estimate the cost of the following items of equipment:

1. A packaged boiler to produce 20,000 kg/h of steam at 40 bar.
2. A centrifugal compressor, driver power 75 kW.
3. A plate and frame filter press, filtration area 10 $m^2$.
4. A floating roof storage tank, capacity 50,000 $m^3$.
5. A cone roof storage tank, capacity 35,000 $m^3$.

**6.8.** A storage tank is purged continuously with a stream of nitrogen. The purge stream leaving the tank is saturated with the product stored in the tank. A major part of the product lost in the purge could be recovered by installing a scrubbing tower to absorb the product in a solvent. The solution from the tower could be fed to a stage in the production process, and the product and solvent recovered without significant additional cost. A preliminary design of the purge recovery system has been made. It would consist of:

1. A small tower 0.5 m diameter, 4.0 m high, packed with 25 mm ceramic saddles, packed height 3.0 m.
2. A small storage tank for the solution, 5 $m^3$ capacity.
3. The necessary pipe work, pump, and instrumentation.

All the equipment can be constructed from carbon steel.

Using the following data, evaluate whether it would be economical to install the recovery system:

1. Cost of product $5 per lb.
2. Cost of solvent $0.5 per lb.
3. Additional solvent make-up 10 kg/d.
4. Current loss of product 0.7 kg/h.
5. Anticipated recovery of product 80 per cent.
6. Additional utility costs, negligible.

Other operating costs will be insignificant.

**6.9.** Make a rough estimate of the cost of steam per ton, produced from a packaged boiler. 10,000 kg per hour of steam are required at 15 bar. Natural gas will be used as the fuel, calorific value 39 $MJ/m^3$ (roughly 1 MMBtu/1000 scf). Take the boiler efficiency as 80 per cent. No condensate will be returned to the boiler.

**6.10.** The production of methyl ethyl ketone (MEK) is described in Appendix F, problem F.3. A preliminary design has been made for a plant to produce 10,000 metric tons per year. The major equipment items required are listed below. The plant operating rate will be 8000 hours per year.

Estimate the capital required for this project, and the cash cost of production.

The plant will be built on an existing site with adequate infrastructure to provide the ancillary requirements of the new plant (no offsite investment is needed).

Major equipment items:

1. Butanol vaporizer: shell and tube heat exchanger, kettle type, heat transfer area 15 $m^2$, design pressure 5 bar, material carbon steel.
2. Reactor feed heaters, (two): shell and tube, fixed head, heat transfer area 25 $m^2$, design pressure 5 bar, material stainless steel.
3. Reactors, (three): shell and tube construction, fixed tube sheets, heat transfer area 50 $m^2$, design pressure 5 bar, material stainless steel.
4. Condenser: shell and tube heat exchanger, fixed tube sheets, heat transfer area 25 $m^2$, design pressure 2 bar, material stainless steel.
5. Absorption column: packed column, diameter 0.5 m, height 6.0 m, packing height 4.5 m, packing 25 mm ceramic saddles, design pressure 2 bar, material carbon steel.
6. Extraction column: packed column, diameter 0.5 m, height 4 m, packed height 3 m, packing 25 mm stainless steel pall rings, design pressure 2 bar, material carbon steel.
7. Solvent recovery column: plate column, diameter 0.6 m, height 6 m, 10 stainless steel sieve plates, design pressure 2 bar, column material carbon steel.
8. Recovery column reboiler: thermosyphon, shell and tube, fixed tube sheets, heat transfer area 4 $m^2$, design pressure 2 bar, material carbon steel.
9. Recovery column condenser: double-pipe, heat transfer area 1.5 $m^2$, design pressure 2 bar, material carbon steel.
10. Solvent cooler: double pipe exchanger, heat transfer area 2 $m^2$, material stainless steel.
11. Product purification column: plate column, diameter 1 $m^2$, height 20 m, 15 sieve plates, design pressure 2 bar, material stainless steel.
12. Product column reboiler: kettle type, heat transfer area 4 $m^2$, design pressure 2 bar, material stainless steel.
13. Product column condenser: shell and tube, floating head, heat transfer area 15 $m^2$, design pressure 2 bar, material stainless steel.
14. Feed compressor: centrifugal, rating 750 kW.
15. Butanol storage tank: cone roof, capacity 400 $m^3$, material carbon steel.
16. Solvent storage tank: horizontal, diameter 1.5 m, length 5 m, material carbon steel.
17. Product storage tank: cone roof, capacity 400 $m^3$, material carbon steel.

*Raw materials*

1. 2-butanol, 1.045 kg per kg of MEK, price \$800 per metric ton.
2. Solvent (trichloroethane) make-up 7000 kg per year, price \$1.0/kg.

*Utilities*

1. Fuel oil, 3000 metric tons per year, heating value 45 GJ/metric ton.
2. Cooling water, 120 metric tons per hour.
3. Steam, low pressure, 1.2 metric tons per hour.
4. Electrical power, 1 MW.

The fuel oil is burnt to provide flue gases for heating the reactor feed and the reactor. Some of the fuel requirements could be provided by using the by-product hydrogen. Also, the exhaust flue gases could be used to generate steam. The economics of these possibilities need not be considered.

**6.11.** A plant is proposing to install a combined heat and power system to supply electrical power and process steam. Power is currently taken from a utility company and steam is generated using on-site boilers.

The capital cost of the CHP plant is estimated to be \$23 million. Combined heat and power is expected to give net savings of \$10 million per year. The plant is expected to operate for 10 years after the completion of construction.

Calculate the cumulative net present value of the project, at a discount rate of 12 per cent, using MACRS depreciation with a five-year recovery term. Also, calculate the discounted cash flow rate of return.

Construction will take two years, and the capital will be paid in two equal increments, at the end of the first and second years. The savings (income) can be taken as paid at the end of each year. Production will start on the completion of construction.

**6.12.** A process heat recovery study identifies five potential modifications, none of which are mutually exclusive, with the costs and energy savings given below.

| **Project** | **Capital Cost (MM\$)** | **Fuel Savings (MMBtu/hr)** |
|---|---|---|
| A | 1.5 | 15 |
| B | 0.6 | 9 |
| C | 1.8 | 16 |
| D | 2.2 | 17 |
| E | 0.3 | 8 |

If fuel costs \$6/MMBtu and the plant operates for 350 days/year, which projects have a simple pay-back period less than one year?

What is the maximum 10 year NPV that can be achieved with a 15% interest rate and a 35% tax rate? Assume all the projects can be built immediately, and use MACRS depreciation with a five year recovery term. What combination of projects is selected to meet the maximum NPV?

**6.13.** An electronics company wants to fit a solvent recovery system on the vent gas from its circuit board manufacturing line. The solvent recovery system consists of a chiller, a knockout drum, and an adsorbent bed. The adsorbent is periodically regenerated by circulating hot air over the bed and to the chiller and knockout. After consultation with equipment vendors, the following purchased prices are estimated for the major plant equipment:

| **Item** | **Cost ($)** |
|---|---|
| Chiller | 4,000 |
| Knockout drum | 1,000 |
| Packaged refrigeration plant | 3,000 |
| Adsorbent vessel (x2) | 1,500 each |
| Air blower | 4,000 |
| Air heater | 3,000 |

Estimate the ISBL cost of the plant and the total project cost. If the annual operating costs are $38,000 and the annual savings in recovered solvent are $61,500, what is the IRR of this project?

**6.14.** Carry out a sensitivity analysis of the adipic acid project described in Examples 6.11 and 6.12.

**6.15.** The adipic acid plant described in Examples 6.11 and 6.12 is to be built in China, with a location factor of 0.85. Up to 45% of the total investment can be secured as a low-cost loan at an interest rate of 1%.

1. What is the cost of capital if the cost of equity is 40%?
2. What is the NPV for 15 years of production?
3. What is the IRR if the debt must be amortized over 15 years as a fixed cost of production?