Part II

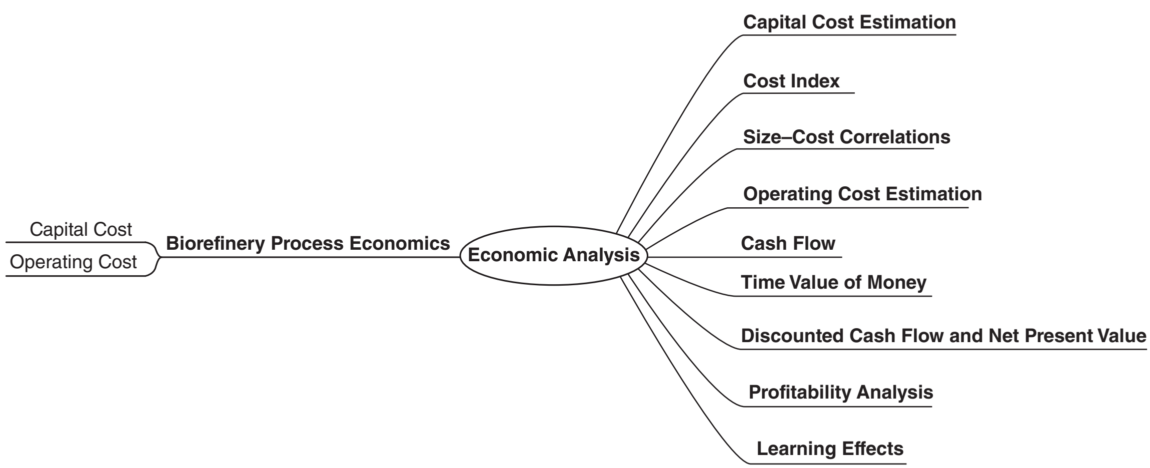
Tools

Biorefineries and Chemical Processes: Design, Integration and Sustainability Analysis, First Edition.
Jhuma Sadhukhan, Kok Siew Ng and Elias Martinez Hernandez.

Companion Website: http://www.wiley.com/go/sadhukhan/biorefineries

2

Economic Analysis



Structure for Lecture Planning

2.1 Introduction

Process economics is one of the crucial aspects for evaluation of process designs. It is often the main criterion in justifying the feasibility of a new design or modification of a plant. Many biomass based technologies are not yet widely employed. This is primarily attributed to the high capital investment and operating costs associated with these technologies, and thus they are less competitive compared to the fossil fuel based technologies. Therefore, it is highly essential to master the skills of performing a proper economic evaluation of a biorefinery plant design in order to gain deeper insights and achieve a better outcome in terms of economics and optimal designs.

This chapter discusses the fundamental concepts of economics germane to chemical engineering process design (Section 2.2) and the methodology for performing economic analysis of process technologies (Section 2.3). The correlation and cost data information of biorefinery design options (Section 2.4) are also shown.

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The learning outcomes from this chapter are as follows.

- To assimilate the fundamental economic terminologies and concepts.
- To perform a capital and operating costs evaluation using the standard techniques, equations, graphs, cost correlations and factors.
- To use economic criteria such as economic potential and netback to justify the economic viability of a design.

2.2 General Economic Concepts and Terminology

2.2.1 Capital Cost and Battery Limits

Capital cost is the cost for building a plant. It can be categorized into two parts: direct and indirect capital costs. Direct capital costs refer to the purchased and installation costs of equipment for constructing a plant. The cost data and correlation for standard equipment can be obtained from various sources including (1) website: *Matches' Process Equipment Cost Estimates*, www.matche.com; (2) reference books: *Coulson & Richardson's Chemical Engineering Design Volume 6, Product & Process Design Principles* and *Guide to Capital Cost Estimating* published by the Institute of Chemical Engineers (IChemE); (3) peer-reviewed archived journals. Most of the equipment costs provided in the literature are the free-on-board (f.o.b.) purchased cost. This means that the delivery cost of equipment is not included. The equipment cost is also influenced by various factors, namely, material of construction, pressure and temperature. These factors need to be considered for each piece of equipment by multiplying the correction factors. The geographical location of a plant is also a highly influential factor for the capital cost due to variations in local regulations, labor, taxes, cost of transportation, etc. A correction factor, if available, should be applied to account for such variations.

Battery limit is used to classify direct capital cost. Inside battery limits (ISBL) comprise the cost of purchasing and installation of major process equipment such as reactors, separators and gas turbines, etc. Other supporting facilities such as utilities and services are considered as outside battery limits (OSBL). Indirect capital costs refer to the design and engineering costs for building a site, contractor's fees and contingency allowances (costs forecasted for some unforeseen circumstances). These are estimated by taking a certain factor on top of the direct capital costs. Working capital should also be included in the capital cost evaluation. It is the cost required for the acquisition of raw materials during the initial start-up stage of a plant, until the plant becomes productive or makes money.

2.2.2 Cost Index

The cost data of equipment obtained for a year is only valid for that particular year. Costs vary with time. Therefore, the cost index method is applied, as shown below for updating the cost taken from previous years and to be used in the current cost analysis:

$$C_{pr} = C_o \left(\frac{I_{pr}}{I_o} \right) \tag{2.1}$$

where

C_{pr} is the present cost
C_o is the original cost
I_{pr} is the present index value
I_o is the original index value.

Many methods to estimate the cost index are available, such as the Chemical Engineering Plant Cost Index (CEPCI), the Marshall and Swift (M&S) Equipment Cost Index, the Nelson-Farrar–(NF) Refinery Construction Cost Index and the Engineering New-Record (ENR) Construction Cost Index. These include the cost index for equipment, labor, engineering and supervision, etc. The Chemical Engineering Plant Cost Index (CEPCI) and the Marshall and Swift (M&S) Equipment Cost Index are used for the cost estimation of biorefineries. Both cost indices are published monthly in *Chemical Engineering*. Figure 2.1 shows the annual CEPCI from year 1996 to 2010.

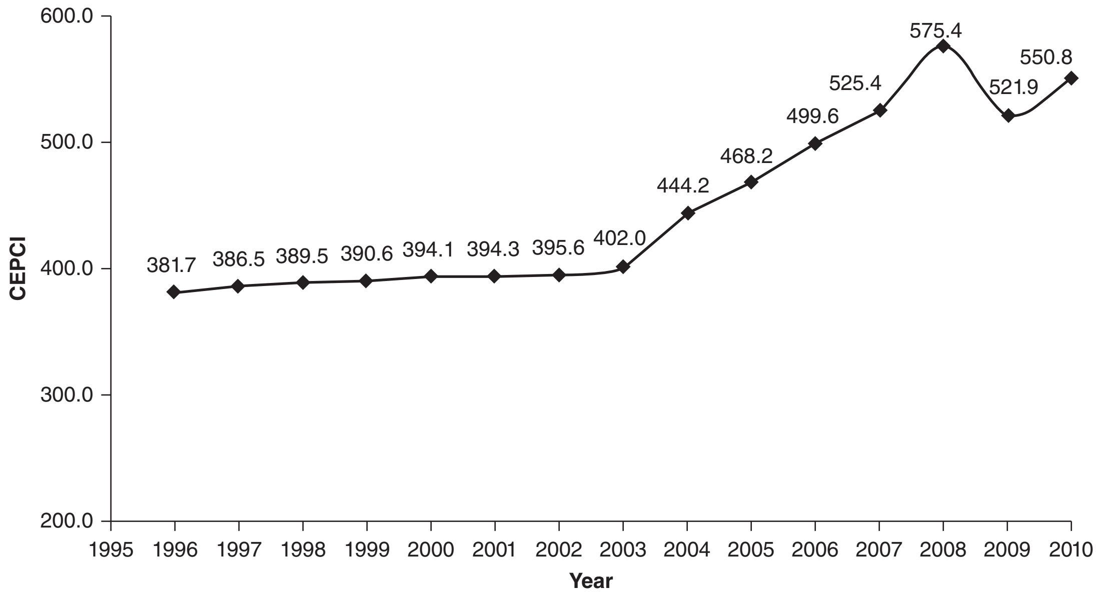

Figure 2.1 *Annual Chemical Engineering Plant Cost Index (CEPCI) from year 1996 to 2010.*

Exercise 1. Calculate the capital cost of two boiler units in year 2010 (CEPCI: 550.8), if the capital cost of one unit was \$0.345 million in year 1998 (CEPCI: 389.5).

Solution to Exercise 1. Using Equation (2.1), the capital cost of one boiler in year 2010 is

$$\begin{aligned} C_{pr} &= C_o\left(\frac{I_{pr}}{I_o}\right) \\ &= 0.345 \times \left(\frac{550.8}{389.5}\right) \\ &= \$0.488 \text{ million} \end{aligned}$$

Hence, two boilers cost: 2 × \$0.488 million = **\$0.976 million** in year 2010.

2.2.3 Economies of Scale

A scaling factor R is applied to estimate the cost of a system based on the known cost of the system for a different size, as shown below. This relationship assumes that the equipment or unit operations can be scaled up/down. The maximum size limit is normally given and multiple units have to be taken into account if the size of the unit exceeds the maximum size.

$$\frac{COST_{size2}}{COST_{size1}} = \left(\frac{SIZE_2}{SIZE_1}\right)^R \tag{2.2}$$

where

$SIZE_1$ is the capacity of the base system
$COST_{size1}$ is the cost of the base system
$SIZE_2$ is the capacity of the system after scaling up/down
$COST_{size2}$ is the cost of the system after scaling up/down
R is the scaling factor.

Exercise 2. Calculate the capital cost of two water gas shift reactors in million $ for a flow rate of 942 kmol h^{-1} through each reactor. The known capital cost of $40.59 million was obtained for a flow rate of 15 600 kmol h^{-1} through one reactor. The scaling factor is 0.85.

Solution to Exercise 2. Using Equation (2.2), the capital cost of one water gas shift reactor in million $ is as follows:

$$\frac{COST_{size2}}{COST_{size1}} = \left(\frac{SIZE_2}{SIZE_1}\right)^R$$

$$COST_{size2} = 40.59 \times \left(\frac{942}{15600}\right)^{0.85} = \$3.73 \text{ million}$$

Hence, the capital cost of two water gas shift reactors is $2 \times 3.73 =$ **$7.46 million**.

2.2.4 Operating Cost

The operating costs can be classified into two main categories: fixed and variable operating costs. Fixed operating costs are independent of the production rate and quantity, in contrast to variable operating costs. These include the costs of maintenance, labor, taxation, insurance, royalties, etc. Fixed operating costs are estimated using factors that are normally based on indirect capital costs. Variable operating costs consist of the costs of raw materials, utilities, etc. The sum of fixed and variable operating costs is the direct production costs (DPCs) of a plant. Other costs such as the costs of research and development, sales expenses and general overheads are added as % of DPC to obtain the total operating cost.

Variable operating costs include the costs of raw materials (e.g., feedstock, catalyst, solvent, etc.) and utilities (e.g., electricity, steam, cooling water, etc.). The costs of raw materials and prices of products are highly volatile, vary with time and thus have the largest impact on the economic performance of a plant in most cases. These values can be obtained from business information providers such as *ICIS Pricing* and *IHS Chemical Week*. The costs of utilities also contribute to a major part of the variable operating costs. These costs vary across organizations. Thus to obtain relevant results, specific information must be collected from associated utility providers.

Table 2.1 shows the factors associated with the fixed cost and other DPC specifications.

Table 2.1 *Cost estimation of fixed operating cost. (Reproduced with permission from Sinnott (2006)[1]. Copyright © 2006, Elsevier: Butterworth-Heinemann.)*

No.	Specification	Cost Estimation
	Fixed Operating Costs	
1	Maintenance	5–10% of indirect capital cost
2	Personnel	See "labor cost" in Section 2.4.2
3	Laboratory costs	20–23% of (2)
4	Supervision	20% of (2)
5	Plant overheads	50% of (2)
6	Capital charges	10% of indirect capital cost
7	Insurance	1% of indirect capital cost
8	Local taxes	2% of indirect capital cost
9	Royalties	1% of indirect capital cost
Direct Production Cost (DPC) = Variable + Fixed Operating Costs		
10	Sales expense	20–30% of DPC
11	General overheads	20–30% of DPC
12	Research and development	20–30% of DPC
	Total operating cost = 1.2 or 1.3 times the DPC	

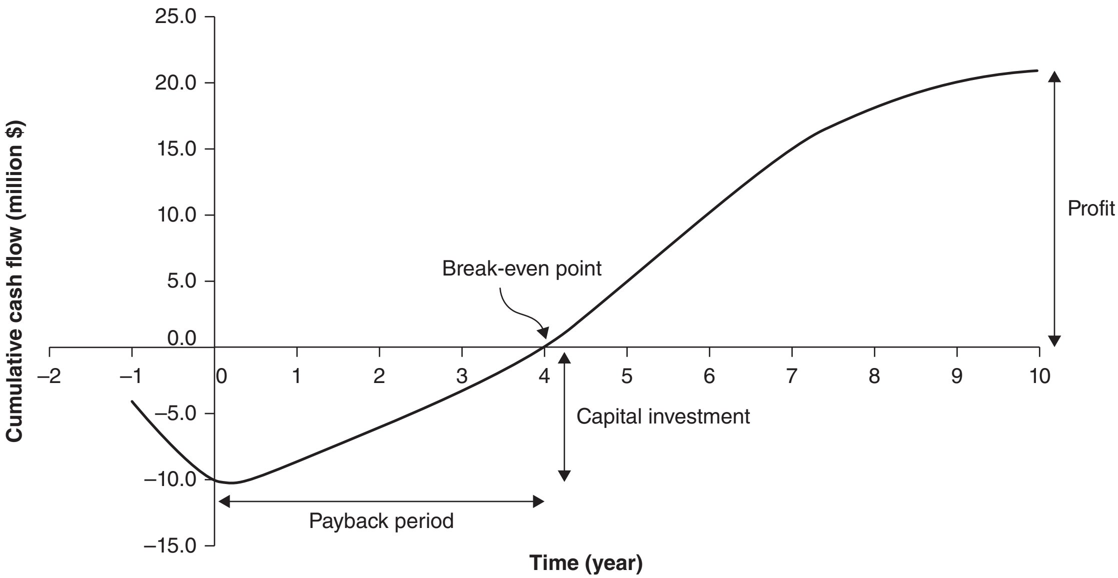

Figure 2.2 Typical cash flow diagram.

2.2.5 Cash Flows

An organization runs its everyday business by relying on a sustainable cash flow. It is thus crucial to understand the input and output of the money flows within an organization. A cash flow diagram, Figure 2.2, shows the capital investment during the initial start-up period (year −1 and 0) and the net cash flow. The net cash flow accounts for the earnings and expenditure over a project lifetime. The process begins at the end of year 0, with a variable yet increasing income until the profits stabilize at around a net cash flow. This relates to the equipment lifespan, increasing production costs and also the market value of the products. The cumulative cash flow remains negative until all the capital investment is reimbursed; this period of time is known as the *payback period*. The cumulative cash flow becomes positive as soon as the plant receives a net positive cash flow from selling products (starting from year 4 in the figure). Having a shorter payback period corresponds to an economically more viable design.

2.2.6 Time Value of Money

The "time value of money" reflects that the present value of money is worthier than the future value of money. For example, \$100 cash that you receive today would have the same amount as the \$100 you would receive after two years, but the "worthiness" of the money is different. If you invest \$100 in a bank at present, you will eventually be getting more than \$100 after two years, due to the addition of the interest paid by the bank. The relationship between present and future values is shown by

$$PV = \frac{FV}{(1 + r)^n} \tag{2.3}$$

where

PV is the present value
FV is the future value
r is the discount rate or interest rate
n is the number of years of investment.

By taking an interest rate of 15% each year, an initial investment of \$100 (present value) will become $\$100 \times (1 + 0.15)^2 = \$132.25$ (future value) after two years. The present value is lower than the future value since the money at present is more valuable than in the future. This is the reason for using the discount rate to predict the "worthiness" of the future money in the present context.

Did you know?

If you win a lottery, it is better to redeem the whole lump sum of money now rather than receiving numerous payments over a few years. This is because the value of the money at present is greater than in the future and the money will depreciate over time. Your money will "shrink"!

2.2.7 Discounted Cash Flow Analysis and Net Present Value

A discounted cash flow (*DCF*) analysis is a method to evaluate the economic potential of an investment, where the projected future value of the cash flow based on capital investment is converted into its present value by applying a discount rate. This analysis considers the aforementioned time value of money.

The cumulative discounted cash flow is expressed as the net present value (*NPV*) in the *DCF* analysis. *NPV* is calculated using the following equation, where C_f is the cash flow in a particular year and T_{PL} is the plant life:

$$NPV = \sum_{n=0}^{n=T_{PL}} \frac{C_f}{(1+r)^n} \tag{2.4}$$

An example of *DCF* analysis is shown in Table 2.2. In this example, the capital investment is assumed to be \$10 million and the cost is distributed over two years, that is, year −1 and 0, by 40% and 60% of the total capital investment, respectively.

In general, *NPV* also serves as an indicator for the profit of a project and thus deciding the feasibility of a particular project; for example, $NPV > 0$ means that the project can bring profits, $NPV < 0$ will result in a loss while $NPV = 0$ represents neither gain nor loss. See Equation (6.7) for a further discussion on calculation of the DCF analysis.

Table 2.2 *An example of DCF analysis for a plant life of 10 years and annual discount rate of 15%.*

Year	Cash Flow (million \$)	Discounted Cash Flow (million \$)	*NPV* (million \$)
−1	−4.0	−4.0	−4.0
0	−6.0	−6.0	−10.0
1	1.5	1.3	−8.7
2	2.5	1.9	−6.8
3	2.8	1.8	−5.0
4	3.2	1.8	−3.1
5	5.0	2.5	−0.6
6	5.0	2.2	1.5
7	5.0	1.9	3.4
8	3.0	1.0	4.4
9	2.0	0.6	4.9
10	1.0	0.2	5.2

Did you know?

Discounted cash flow is strongly associated with our everyday lives. The calculations of the repayments of home mortgage, car loan and credit card are a few applications of discounted cash flow analysis.

Exercise 3. Andy is applying for a housing mortgage from a bank. He intends to borrow \$300 000 where the current annual interest rate offered is 4.0%. The repayment period he has chosen is 30 years with a fixed rate scheme. How much does Andy have to pay monthly? The financial advisor of the bank suggested that he should choose a repayment period of 20 years. What is the benefit of having a shorter repayment period?

Solution to Exercise 3. There are 360 payments in total that need to be made over a 30 year period, that is, 1 year = 12 months. Monthly interest rate is 4/12 = 0.333%.

Method 1. By using the *DCF* method shown in Table 2.2, applying Equation (2.4) and setting $NPV = 0$ at the end of 30 years

or

Method 2. Using the PMT function in Excel, that is, = PMT(0.04/12, 360, −300 000)

Note that the PMT function is a Financial function in Excel that can be used for calculating the periodic payment for a loan based on constant payments and a constant interest rate.

or

Method 3. Using formula

$$\text{Monthly instalment}, M = \frac{P \times r \times (1+r)^N}{[(1+r)^N] - 1} = \frac{P \times \left(\frac{i}{q}\right) \times \left(1 + \frac{i}{q}\right)^N}{\left[\left(1 + \frac{i}{q}\right)^N\right] - 1} \tag{2.5}$$

where

P is the principal of the loan
$r = i/q$, i is the annual interest rate and q is the number of payments a year
N is the number of payments in total.

$$\text{Monthly instalment}, M, \text{ for 30 years} = \frac{300\,000 \times \left(\frac{0.04}{12}\right) \times \left(1 + \frac{0.04}{12}\right)^{360}}{\left[\left(1 + \frac{0.04}{12}\right)^{360}\right] - 1} = \$1432.25$$

There are a total 240 payments that need to be made over the 20 years period, that is, 1 year = 12 months. The monthly interest rate is 4/12 = 0.333%.

$$\text{Monthly instalment, } M \text{ for 20 years} = \frac{300\,000 \times \left(\frac{0.04}{12}\right) \times \left(1 + \frac{0.04}{12}\right)^{240}}{\left[\left(1 + \frac{0.04}{12}\right)^{240}\right] - 1} = \$1817.94$$

The monthly repayment for the 30 years period is estimated to be **$1432.25**.
If the 20 years repayment period is chosen, the monthly repayment would be **$1817.94**.
Total interest paid can be determined using

$$\text{Total interest paid}, I_T = (M \times n \times q) - P \tag{2.6}$$

$$\text{Total interest paid}, I_T \text{ for 30 years} = (1432.25 \times 30 \times 12) - 300\,000 = \$215\,610$$

$$\text{Total interest paid}, I_T \text{ for 20 years} = (1817.94 \times 20 \times 12) - 300\,000 = \$136\,305.60$$

The total amount of interest paid over 30 years and 20 years are **$215 610** and **$136 305.60**, respectively. Therefore, the financial advisor was right! A shorter repayment period will incur less amount of interest. In this case, **$79 304.40** savings can be achieved.

Note that the monthly instalment is also known as the EMI (equated monthly instalment). Sometimes, processing fees are included, for example, for a mortgage payment. This should be accounted as part of the loan. The APR (annual percentage rate) is normally used as an indicator to compare among different schemes with different interest rates and processing fees.

2.2.8 Profitability Analysis

A profitability analysis is essential to justify the economic feasibility of a project. This can be carried out using various methods and measures, depending on the level of details required. During the preliminary stage of a project, the time value of money is not considered. The approximate quantitative indicators at the preliminary stage are payback time, return on investment and total annualized cost.

Payback time is the period from the start of a project until the time when all capital investment is recovered from selling of products (breakeven), shown in Figure 2.2. Intuitively, a shorter payback time is preferred. However, the usefulness of the payback time as an indicator is limited since it is only valid up to the break-even point. The economic performance after the break-even point cannot be measured using this indicator.

Return on investment (*ROI*) is a common profitability measure of a project, defined as the ratio of the annual income over a project life to the total capital investment, shown below. *ROI* gives a sense of the efficiency of an investment being made:

$$ROI = \frac{\text{Annual income}}{\text{Capital investment}} \times 100\% \tag{2.7}$$

The discounted cash flow rate of return (DCFRR) is essentially the interest rate that makes the *NPV* zero at the end of a project. The DCFRR is a way to measure the performance of utilizing a capital for projects, but does not give any indication of the profit, unlike the *NPV*. The DCFRR can be calculated using Equation (2.4) through the trial-and-error method (e.g., using the Solver function in Excel or the iteration method) or the graphical method.

The total annualized cost includes capital and operating costs in most of the cases, shown in the following equation. The annualized capital cost can be estimated using a fixed interest rate over the plant life. The operating cost is estimated by assuming operating hours in a year.

$$\text{Total annual cost} = \text{Annualized capital cost} + \text{Annual operating cost} \tag{2.8}$$

A more rigorous profitability analysis considering the time value of money is desirable in the detailed process design stage. Economic criteria such as economic potential, netback and cost of production can be applied.

Economic potential (*EP*) is the economic margin and can be evaluated using the following equation when values of products, feed, capital cost and operating cost are available. To obtain an annualized capital cost with the consideration of time value of money, the DCFRR needs to be calculated using Equation (2.4) by setting $NPV = 0$.

$$EP = \text{Value of products} - (\text{Value of feed} + \text{Annualized capital cost} + \text{Annual operating cost}) \tag{2.9}$$

Netback indicates the value of a feedstock from its products selling and can be determined using the following equation. Product prices, capital cost and operating cost except the feedstock cost are known. The market price or cost of the feedstock thus must be less than the netback to result in a positive economic margin.

$$\text{Netback} = \text{Value of products} - (\text{Annualized capital cost} + \text{Annual operating cost}) \tag{2.10}$$

Cost of production of a product is a meaningful indicator when comparing the economic viability between various production routes. It is used when the value of a product is not known, especially when a new product is synthesized or a conventional product is generated from a nonconventional feedstock. The cost of production is calculated from

$$\text{Cost of production} = \frac{\text{Value of feed} + \text{Annualized capital cost} + \text{Annual operating cost}}{\text{Production rate}} \tag{2.11}$$

2.2.9 Learning Effect

The cost of a new and developing technology such as fast pyrolysis of biomass and gasification of biomass is usually very high in the beginning of the development stage. The cost of the technologies decreases as more plants are built and productivity increases due to more experience gain by organizations. This effect is known as a *learning curve* or *experience curve* or *progress curve* or *learning by doing effect*, as shown in Figure 2.3.

The trend of the learning curve can be described by

$$y = a\,x^{-b} \tag{2.12}$$

where y is the cost of the xth unit, a is the cost of the first unit, x is the cumulative number of units and b is a parameter shown as $b = \log$ (progress ratio)/log 2.

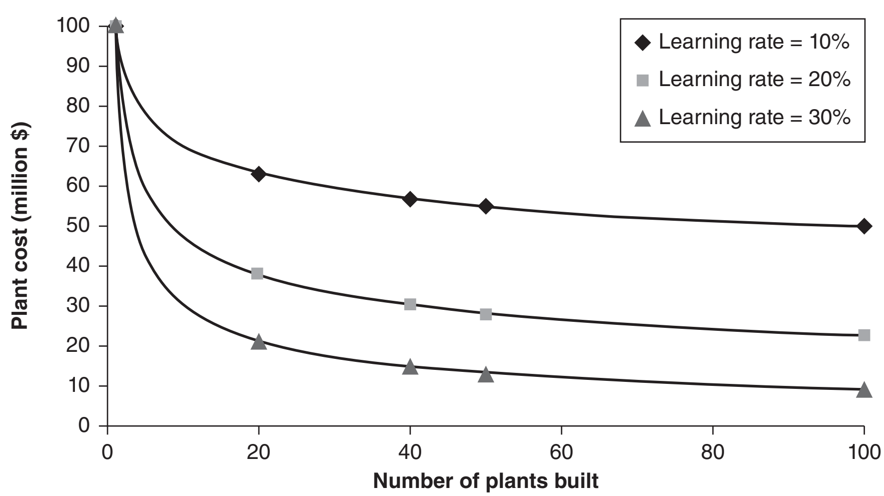

Figure 2.3 *Learning curve effect.*

The learning rate is shown by

$$\text{Learning rate} = 1 - (\text{Progress ratio}) \tag{2.13}$$

The rates of learning vary across different organizations. The factors influencing the rate of learning are crucial and particular attention has to be paid to enhance the performance and economics of the plant. A few factors have been identified as follows:

- Organization forgetting
- Employee turnover
- Transfer of knowledge
- Failure to control other factors such as economies of scale.

The learning curve effect and the learning rate can be easily understood by visualizing the teaching and learning environment in a classroom. If there are 30 students in a classroom, the amount of material that can be assimilated varies from individual to individual, assuming they have no background knowledge on a particular subject and the time of learning is the same. In this case, the method of learning, individual ability and attitude are variables.

2.3 Methodology

2.3.1 Capital Cost Estimation

There is extensive published literature reporting the correlations for estimating the cost of standard equipment, for example, heat exchangers, boilers, turbines, pumps, etc. This information is normally enough for carrying out a chemical plant economics evaluation. However, for a plant undergoing development, such as the biorefinery systems, much of the cost data is unavailable, not readily accessible or may be proprietarily to organizations. Therefore, the costs of equipment may need to be estimated based on existing methodologies or vendor quotes of similar equipment. The Aspen Icarus process evaluator is widely used for an equipment cost estimation in industry. The software may not be available with academic and small organizations; hence spreadsheet based economic evaluation is more convenient and still preferable.

The approach for estimating the equipment cost presented here has avoided using a cost chart that may lead to inconsistent results. A set of established information on equipment costs for biorefinery systems is used as the base cost and the suggested methodology is to scale up or down according to the desired capacity. The base costs and scale factors are collected from various sources[2–7].

The capital cost can be estimated using different methods, that is, order of magnitude estimate, study estimate, preliminary estimate, definitive estimate and detailed estimate. These methods need information at different levels of detail, hence leading to different levels of accuracy. A capital cost estimation by the order of magnitude results in an accuracy of 30–50%. The definitive and detailed estimates require Aspen Icarus software and also a vendor's quote, and thus are more complicated. For these reasons, study and preliminary estimates are preferable since they involve moderate complexity while giving accuracy at a reasonable level. The recommended capital cost estimation approaches are Guthrie's[8] and Lang's[9] methods, able to achieve an accuracy of 20–30%. These approaches should be used for a new design and more time should be allowed to complete the evaluation since many details are required, that is, a complete flowsheet with mass and energy balances, equipment sizing, etc.

The recommended approach for estimating capital costs is shown as follows:

1. Generate a list of equipment and estimate the size of each piece of equipment. The size information in terms of flow rates and power requirements (e.g., for pumps and compressors, etc.) can be obtained directly from simulation. However, some equipment require additional sizing procedures, such as weight of vessel and heat transfer area of the heat exchanger.
2. By applying the concept of economies of scale (Equation (2.2)), the base cost of equipment with a specific size is scaled up/down to obtain the cost of equipment for a desired size. Refer to Table 2.3 (gasification and hydrocracking systems) and Table 2.4 (bioethanol system) for information on base sizes, base costs and scale factors.
3. If the desired size of equipment exceeds the maximum size given, multiple units have to be assumed.

4. Apply the correction factors to the cost of equipment (where relevant) depending upon the material of construction, pressure and temperature.
5. The estimated cost of a piece of equipment can be obtained for different years. Therefore it has to be updated to the cost at the current year, by adopting Equation (2.1) and the cost index in Figure 2.1.
6. Estimate the total capital investment of the system, either based on the individual factor method (Guthrie's method) or the overall factor method (Lang's method).
   a. Guthrie's method. The cost of equipment is given in terms of the f.o.b. purchased cost. Apply individual installation factors for each unit operation to determine the total capital investment.
   b. Lang's method. The cost of equipment is given in terms of the f.o.b. purchased cost. Assume 10% delivery charges as a preliminary estimation. Calculate the total installed cost of equipment using an overall Lang factor based on the plant type, shown in Table 2.5.

For technologies at an early development stage, the estimated cost is normally very high. The learning curve effect (Equation (2.12)) can be taken into account to forecast the future cost of a system and to obtain a reasonable estimation of the cost. A reasonable reference point is the cost of building the tenth plant ($x = 10$ in Equation (2.12)) and a progress ratio of 0.8 can be used as a preliminary estimation.

Remarks. The Golden Rule: an estimated capital cost of a facility is unlikely to give its actual value. No matter how sophisticated the capital cost estimation method is, it will never be accurate. It is not possible to apply the same values for different locations and time. However, an estimated cost needs to be reasonable. Aspen Icarus is widely accepted and has been a standard in the chemical industry due to its strength in performing sizing and costing of equipment. Vendor's quotes are more up-to-date, yet it is still unreliable at some point due to several factors such as the seller-and-buyer relationship, contemporary supply and demand, etc. It is advisable to use the same basis throughout a capital cost evaluation of equipment in a plant so that the same degree of accuracy can be attained. A sensitivity analysis should be carried out to examine the effects of inaccuracies on results.

2.3.2 Profitability Analysis

The economic feasibility of a plant can be examined using the economic criteria mentioned in Section 2.2. A systematic approach is provided as a guideline to evaluate the economic performance of a plant up to a reasonably detailed level, as follows:

1. Evaluate the capital cost using the procedures given in Section 2.3.1. The annualized capital cost is calculated using the discounted cash flow (*DCF*) analysis (Section 2.2.7), by assuming a reasonable plant life.
2. Evaluate the annual operating cost. Variable operating costs such as biomass feedstock and transportation costs are shown in Tables 2.6 and 2.7, respectively, and the costs of chemicals and utilities can be obtained conveniently elsewhere. The cost factors for fixed operating costs are shown in Table 2.1.
3. Select an indicative economic measure, that is, economic potential, netback and cost of production, and determine the economic performance of the plant.

2.4 Cost Estimation and Correlation

The correlations for estimating the capital and operating costs of biorefinery systems are shown in Sections 2.4.1 and 2.4.2, respectively.

2.4.1 Capital Cost

The parameters required for estimating the equipment cost (base scales, base costs and scale factors) of gasification, hydrocracking and bioethanol systems[2–7] are shown in Tables 2.3 and 2.4, respectively. The installation factors for

Table 2.3 Equipment cost correlation – gasification and hydrocracking systems[2–4,6,7].

Item No.	Component	Base cost (million $)	Scale Factor	Base Size	Capacity	Maximum Size	Installation Factor	Base Year
A. Pretreatment								
A.1	Conveyers	0.35	0.8	33.5	wet t h^{-1} biomass feed	110	1.86	2001
A.2	Grinding	0.41	0.6	33.5	wet t h^{-1} biomass feed	110	1.86	2001
A.3	Storage	1.0	0.65	33.5	wet t h^{-1} biomass feed	110	1.86	2001
A.4	Dryer	7.6	0.8	33.5	wet t h^{-1} biomass feed	110	1.86	2001
A.5	Iron removal	0.37	0.7	33.5	wet t h^{-1} biomass feed	110	1.86	2001
A.6	Feeding system	0.41	1.0	33.5	wet t h^{-1} biomass feed	110	1.86	2001
B. Gasification System								
B.1	Gasifier BCL[a]	16.3	0.65	68.8	dry t h^{-1} biomass feed	83	1.69	2001
B.2	Gasifier IGT[b]	38.1	0.7	68.8	dry t h^{-1} biomass feed	75	1.69	2001
C. Syngas Cleaning								
C.1	Tar cracker	3.1	0.7	34.2	m^3 s^{-1} gas input	52	1.86	2001
C.2	Cyclones	2.6	0.7	34.2	m^3 s^{-1} gas input	180	1.86	2001
C.3	Gas cooling	6.99	0.6	39.2	kg s^{-1} steam generation		1.84	2001
C.4	Baghouse filter	1.6	0.65	12.1	m^3 s^{-1} gas input	64	1.86	2001
C.5	Condensing scrubber	2.6	0.7	12.1	m^3 s^{-1} gas input	64	1.86	2001
C.6	Hot gas cleaning	30	1.0	74.1	m^3 s^{-1} gas input		1.72	2001
D. Syngas Processing								
D.1	Steam reformer	9.4	0.6	1390	kmol h^{-1} gas input		2.3	2001
D.2	Autothermal reformer	4.7	0.6	1390	kmol h^{-1} gas input		2.3	2001
D.3	Shift reactor	36.9	0.85	15.6	Mmol h^{-1} CO+H_2 input		1.0	2001
D.4	Selexol CO_2 removal	54.1	0.7	9909	kmol h^{-1} CO_2 removed		1.0	2001
E. Product Synthesis and Upgrading								
E.1	Solid bed FT gas phase 60 bar	25.3	1.0	100	MW (HHV) FT produced		1.3	2001
E.2	Slurry phase FT 60 bar	36.5	0.72	131	MW (HHV) FT produced		1.0	2001
E.3	FT product upgrading	233	0.7	286	m^3 h^{-1} FT produced		1.0	2001
E.4	Gas phase methanol synthesis reactor	7	0.6	87.5	t h^{-1} MeOH produced		2.1	2001
E.5	Liquid phase methanol synthesis reactor	3.5	0.72	87.5	t h^{-1} MeOH produced		2.1	2001
E.6	Methanol product upgrading	15.1	0.7	87.5	t h^{-1} MeOH produced		2.1	2001
F. Combined Cycle								
F.1	Gas turbine + HRSG	18.9	0.7	26.3	MW_e electrical output		1.86	2001
F.2	Steam turbine and steam system	5.1	0.7	10.3	MW_e electrical output		1.86	2001
G. Common Process Machinery								
G.1	Compressor	11.1	0.85	13.2	MW_e compression work		1.72	2001
H. Separation Unit								
H.1	Oxygen plant	44.2	0.85	41.7	t h^{-1} O_2 produced		1.0	2001
H.2	Pressure swing adsorption (PSA) unit[c]	28	0.7	9600	kmol h^{-1} throughput		1.69	2001
H.3	Membrane[c]	21.6	0.8	17	t h^{-1} H_2 recovered		1.0	2001
I. Pyrolysis Unit								
I.1	Pyrolyzer (circulating fluidized bed)	3.392	0.7	500	t d^{-1} biomass feed		2.47	2003
J. Refinery Unit								
J.1	Hydrocracker unit[d]	30	0.65	2250	bbl d^{-1} pyrolysis oil feed		2.47	2005
J.2	Separation[e]	2.28	0.65	2250	bbl d^{-1} pyrolysis oil feed		1.0	2007

[a] Gasifier BCL (Batelle Columbus) is an indirect, air-blown and atmospheric gasifier.
[b] Gasifier IGT (Institute of Gas Technology) is a direct, oxygen-blown and pressurized gasifier.
[c] Pressure swing adsorption unit and membrane are employed for hydrogen recovery process.
[d] Hydrocracker unit consists of fired heater, hydrocracker vessel, feed/product exchanger, air cooler, trim cooler, high and low pressure flash.
[e] Separation units include fractionators, splitters, reboilers, condensers and reflux drums.

Notes:
FT: Fischer–Tropsch (c.f. Chapter 14).
HRSG: heat recovery steam generator.
HHV: higher heating value (c.f. Section 10.2.2).

Table 2.4 *Equipment cost correlation – bioethanol system*[5].

Item No.	Component	Base Cost (million $)	Scale Factor	Base Size	Capacity	Maximum Size	Installation Factor	Base Year
A. Pretreatment								
A.1	Mechanical	4.44	0.67	83.3	dry t h^{-1} biomass feed	83.3	2.00	2003
A.2	Mill	0.37	0.7	50	wet t h^{-1} biomass feed		1.00	2003
A.3	Dilute acid	14.1	0.78	83.3	dry t h^{-1} biomass feed		2.36	2003
A.4	Steam explosion	1.41	0.78	83.3	dry t h^{-1} biomass feed		2.36	2003
A.5	Liquid hot water	5.62	0.78	83.3	dry t h^{-1} biomass feed		2.36	2003
A.6	Ion exchange	2.39	0.33	83.3	dry t h^{-1} biomass feed		1.88	2003
A.7	Overliming	0.77	0.46	83.3	dry t h^{-1} biomass feed		2.04	2003
B. Hydrolysis and Fermentation								
B.1	Cellulase production (SSF)	1.28	0.8	50	kg h^{-1} cellulase produced	50	2.03	2003
B.2	Seed fermenters (SSF+SSCF)	0.26	0.6	3.53	t h^{-1} ethanol produced	3.53	2.20	2003
B.3	C5 fermentation (SSF)	0.67	0.8	1.04	t h^{-1} ethanol produced	1.04	1.88	2003
B.4	Hydrolyze-fermentation (SSF)	0.67	0.8	1.04	t h^{-1} ethanol produced	1.04	1.88	2003
B.5	SSCF	0.67	0.8	1.04	t h^{-1} ethanol produced	1.04	1.88	2003
B.6	CBP	0.67	0.8	1.04	t h^{-1} ethanol produced	1.04	1.88	2003
C. Upgrading								
C.1	Distillation and purification	2.96	0.7	18.466	t h^{-1} ethanol produced	18.466	2.75	2003
C.2	Molecular sieve	2.92	0.7	18.466	t h^{-1} ethanol produced	18.466	1.00	2003
D. Residuals								
D.1	Solids separation	1.05	0.65	10.1	dry t h^{-1} solids	10.1	2.20	2003
D.2	(An)aerobic digestion	1.54	0.6	43	t h^{-1} wastewater	43	1.95	2003

Notes:
SSF: simultaneous saccharification and fermentation.
SSCF: simultaneous saccharification and co-fermentation.
CBP: consolidated bioprocessing.

Table 2.5 *Typical Lang factors of various plants for estimating capital investment based on the delivered cost of equipment*[9].

Plant	Solid Processing	Solid–Fluid Processing	Fluid Processing
Direct Cost			
Delivered cost of equipment	1.00	1.00	1.00
Installation	0.45	0.39	0.47
Instrumentation and control	0.18	0.26	0.36
Piping	0.16	0.31	0.68
Electrical systems	0.10	0.10	0.11
Buildings (including services)	0.25	0.29	0.18
Yard improvements	0.15	0.12	0.10
Service facilities	0.40	0.55	0.70
Total direct cost, C_D	**2.69**	**3.02**	**3.60**
Indirect Cost			
Engineering and supervision	0.33	0.32	0.33
Construction expenses	0.39	0.34	0.41
Legal expenses	0.04	0.04	0.04
Contractor's fee	0.17	0.19	0.22
Contingency	0.35	0.37	0.44
Total indirect cost, C_{ID}	**1.28**	**1.26**	**1.44**
Working capital	0.7	0.75	0.89
Total capital investment, C_{TCI}	**4.67**	**5.03**	**5.93**

individual equipment are required in Guthrie's method. These factors have taken into account the direct and indirect cost components, but with different assumptions compared to the Lang factor and also working capital is not included. The Lang factors depending upon plant types are shown in Table 2.5.

2.4.2 Operating Cost

The variable operating costs of biorefinery systems include the costs of raw materials (e.g., feedstock, chemical, catalyst, etc.), utilities (e.g., electricity, steam, etc.) and transportation. These are highly dependent on process specification and preferences. Most of the prices of chemicals can be easily obtained from published literature and online resources. Therefore, only the biomass prices (Table 2.6) and its transportation costs (Table 2.7) are shown for year 2007[10].

Table 2.6 *Estimated prices of various biomass feedstocks. (Reproduced with permission from Department of Trade and Industry (2007)[10].)*

Biomass	Central Price ($ GJ^{-1})	Price Range ($ odt^{-1})	($ GJ^{-1})
Forestry woodfuel-chips	5	120	4.0–6.0
Forestry woodfuel-logs	4	80	3.0–5.0
Energy crops			
Short rotation coppice (SRC)	7	140	6.0–8.0
Miscanthus	6	106	5.0–7.0
Arboricultural arisings	5	98	4.0–6.0
Straw	4	70	3.0–5.0
Waste wood (clean)	5	98	4.0–6.0
Waste wood (contaminated)	2	40	1.0–3.0
Pellets to power/industry/commercial from woodfuel	9	180	8.0–10.0
Pellets to power/industry/commercial from SRC	11	220	10.0–12.0
Pellets to power/industry/commercial from miscanthus	10	200	9.0–11.0
Pellets to domestic (including delivery)	14	280	12.0–16.0
Imported biomass (including delivery)	9	180	7.0–11.0

Note: odt = oven dry tonne.

Table 2.7 *Estimated average transportation costs for different biomass feedstocks. (Reproduced with permission from Department of Trade and Industry (2007)[10].)*

	Transportation Cost ($ GJ^{-1})		
Application	Energy Crops	Woodfuel	Straw
Power generation			
1% co-firing, 2000 MW	NA	0.60 (17)	0.60 (17)
5% co-firing, 2000 MW	1.0 (35)	NA	1.60 (52)
10% co-firing, 2000 MW	1.32 (49)	NA	NA
30 MW dedicated	0.72 (24)	0.74 (25)	0.76 (28)
Heat			
0.1–10 MW of heat generation	0.60 (17)	0.60 (17)	NA
CHP			
0.1–10 MW of electricity generation	0.60 (17)	0.60 (17)	NA
> 10 MW of electricity generation	0.72 (24)	0.74 (25)	0.76 (28)

Note: Numbers in parentheses are estimated average transport distance in km. NA = not assessed.

Table 2.8 *Personnel requirement for chemical processing plants. (Reproduced with permission from Seider et al. (2010)[11]. Copyright © 2010, John Wiley & Sons, Ltd.)*

Process	Number of Personnel per Processing Step
Continuous	
i. Fluids processing	1
ii. Solids–fluids processing	2
iii. Solids processing	3
Batch/semi-batch	
i. Fluids processing	2
ii. Solids–fluids processing	3
iii. Solids processing	4

The cost of labor/personnel is difficult to estimate since it is dissimilar from one organization to another. Furthermore, it varies across different chemical sectors (e.g., petroleum and pharmaceutical), different countries and even different locations. Additionally, the personnel position also determines the salary that they earn. For preliminary estimation purposes, the following approach can be used to estimate the cost of labor.

Step 1. Calculate the number of personnel per shift using Equation (2.14)

The operating labor requirement is related to the number of processing steps depending on the process, as shown in Table 2.8. The number of personnel per processing step is also shown:

$$\begin{aligned}\text{Number of personnel per shift} &= \text{Number of processing steps}\\ &\quad\times \text{Number of personnel per processing step}\end{aligned} \tag{2.14}$$

The number of personnel per processing step should be doubled when the size of the continuous process is large, that is, greater than 1000 t d^{-1} of product[11].

Step 2. Calculate the cost of personnel using Equation (2.15)

$$\begin{aligned}\text{Cost of personnel } (\$\ \text{y}^{-1}) &= \text{Number of personnel per shift} \times 5 \text{ shifts} \times 40 \text{ hours/week} \times 52 \text{ weeks/year}\\ &\quad\times \text{hourly wages } (\$\ \text{h}^{-1})\end{aligned} \tag{2.15}$$

Assume 5 shifts per day are required. Each personnel works 40 hours per week and there are 168 hours per week. In addition, consider other factors such as sick leaves, holidays, etc.

The Bureau of Labor Statistics in the US Department of Labor estimated that the mean hourly wages for a chemical engineer in year 2008 is at the rate of \$42.67 (€29) per hour.

2.5 Summary

This chapter shows the generic economic analysis concept and fundamental teaching and learning tools for chemical engineering process economics. The time value of money and discounted cash flow are among the important aspects in an economic evaluation. The methods for analyzing capital cost and operating cost have been outlined and translated into easy-to-follow procedures, accompanied by cost estimation correlation and data.

2.6 Exercises

Refer to the ***Online Resource Material, Chapter 2 – Additional Exercises and Examples***, the solutions to all Exercise problems.

1. A company is planning to start a methanol production plant via thermochemical conversion of biomass. The plant encompasses the following main equipment:
- Dryer
- Gasifier (direct, oxygen-blown and pressurized)
- Oxygen plant
- Tar cracker
- Water gas shift reactor
- Methanol synthesis reactor (gas phase)

Process specifications and assumptions:
- Biomass feed = 150 dry t h^{-1}
- Moisture content of biomass = 30 wt%
- Oxygen requirement in gasifier = 0.45 kg kg^{-1} dry biomass feedstock
- Yield of product gas from gasification = 100 kmol t^{-1} dry biomass feedstock
- Standard molar volume of gas = 22.414 m^3 $kmol^{-1}$
- Mole fraction of components in product gas

$$CO = 0.15;\ H_2 = 0.20$$

- Higher heating value (HHV) of

$$\text{Biomass} = 20\,\text{MJ kg}^{-1}$$

$$\text{Methanol} = 23\,\text{MJ kg}^{-1}$$

- Output efficiency = 45% based on HHV
  a. Calculate the purchased cost of each individual piece of equipment and hence the total purchased cost of equipment of the methanol production system.
  b. Calculate the total capital investment of the methanol production plant by applying Guthrie's method.
  c. The cost of equipment is valid in year 2001. Estimate the total cost of equipment in year 2010 using the Chemical Engineering Plant Cost Index.

2. The methanol production plant requires steam and electricity to run the process. It has been estimated that 2.0 kg of steam per kg of methanol produced is needed for the whole system while 235 kW h of electricity per tonne of O_2 are needed for the oxygen plant.

a. Calculate the utility cost required per annum for this plant using the results calculated from Question 1.
b. If heat integration is applied on this plant, steam can be generated through heat exchange with process streams. The steam requirement can then be partially satisfied by the steam generated on site. It has been estimated that 40% of the imported steam can be reduced. Calculate the % cost saving from heat integration relative to the steam import scenario.

Assumptions:
- 8000 operating hours per year
- Cost of imported steam = \$15 t^{-1}
- Cost of imported electricity = \$0.1 kW h^{-1}

3. The company is at the stage of choosing between two plant options, X and Y. The finance department has provided an estimation of the annual cash flow for a period of 10 years, shown in Table 2.9. Evaluate both options with respect to:

a. Payback time.
b. Return on investment.

Table 2.9 Cash flow for two plant options.

	Cash Flow (million $)	
Year	Option X	Option Y
−1	−40.0	−40.0
0	−60.0	−60.0
1	30.0	5.0
2	40.0	15.0
3	50.0	25.0
4	65.0	40.0
5	70.0	50.0
6	75.0	65.0
7	85.0	75.0
8	90.0	75.0
9	90.0	80.0
10	90.0	80.0

c. Discounted cash flow and net present value for each year. Assume an annual discount rate of 10%.
d. Discounted cash flow rate of return.
e. Suggest the preferred option based on the results obtained from (a), (b) and (c) and (d).
f. Illustrate the effect of having different annual discount rates, that is, 5% and 20%, on the overall economic performance of the preferred option in *NPV* versus time plot and draw conclusions based on the trend.

4. By using the results obtained from Questions 1 and 2(b), show the netback calculation to estimate the value of the biomass feedstock. Assume a DCFRR of 15% for the annualized capital cost.

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