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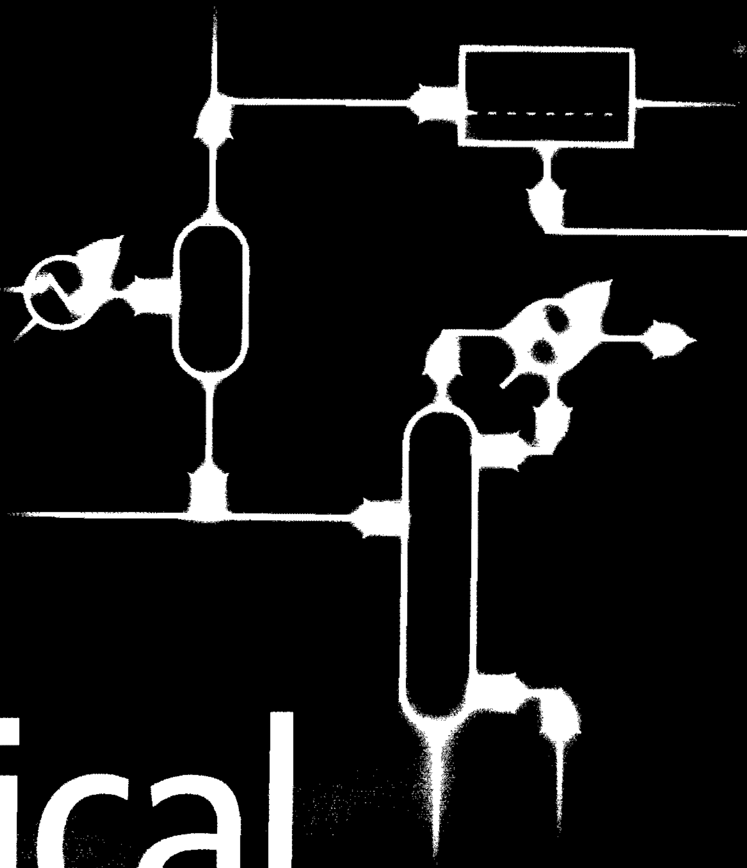

Chemical Process

DESIGN AND INTEGRATION

WILEY

2 Process Economics

2.1 THE ROLE OF PROCESS ECONOMICS

The purpose of chemical processes is to make money. An understanding of process economics is therefore critical in process design. Process economics has three basic roles in process design:

1. *Evaluation of design options*. Costs are required to evaluate process design options; for example, should a membrane or an adsorption process be used for purification?
2. *Process optimization*. The settings of some process variables can have a major influence on the decision-making in developing the flowsheet and on the overall profitability of the process. Optimization of such variables is usually required.
3. *Overall project profitability*. The economics of the overall project should be evaluated at different stages during the design to assess whether the project is economically viable.

Before discussing how to use process economics for decision-making, the most important costs that will be needed to compare options must first be reviewed.

2.2 CAPITAL COST FOR NEW DESIGN

The total investment required for a new design can be broken down into five main parts:

- Battery limits investment
- Utility investment
- Off-site investment
- Engineering fees
- Working capital.

1. *Battery limits investment*: The battery limit is a geographic boundary that defines the manufacturing area of the process. This is that part of the manufacturing system that converts raw materials into products. It includes process equipment and buildings or structures to house it but excludes boiler-house facilities, site storage, pollution control, site infrastructure, and so on. The term battery limit is sometimes used to define the boundary of responsibility for a given project, especially in retrofit projects.

The battery limit investment required is the purchase of the individual plant items and their installation to form a working process. Equipment costs may be obtained from equipment vendors or from published cost data. Care should be taken as to the basis of such cost data. What is required for cost estimates is delivered cost, but cost is often quoted as FOB (Free On Board). Free On Board means the manufacturer pays for loading charges onto a shipping truck, railcar, barge or ship, but not freight or unloading charges. To obtain a delivered cost requires typically 5 to 10% to be added to the FOB cost. The delivery cost depends on location of the equipment supplier, location of site to be delivered, size of the equipment, and so on.

The cost of a specific item of equipment will be a function of:

- size
- materials of construction
- design pressure
- design temperature.

Cost data are often presented as cost versus capacity charts, or expressed as a power law of capacity:

$$C_E = C_B \left(\frac{Q}{Q_B} \right)^M \tag{2.1}$$

where C_E = equipment cost with capacity Q
C_B = known base cost for equipment with capacity Q_B
M = constant depending on equipment type

A number of sources of such data are available in the open literature[1-8]. Published data are often old, sometimes from a variety of sources, with different ages. Such data can be brought up-to-date and put on a common basis using cost indexes.

$$\frac{C_1}{C_2} = \frac{INDEX_1}{INDEX_2} \tag{2.2}$$

where C_1 = equipment cost in year 1
C_2 = equipment cost in year 2
$INDEX_1$ = cost index in year 1
$INDEX_2$ = cost index in year 2

Commonly used indices are the Chemical Engineering Indexes (1957–1959 index = 100) and Marshall and Swift (1926 index = 100), published in *Chemical Engineering*

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Table 2.1 Typical equipment capacity delivered capital cost correlations.

Equipment	Material of construction	Capacity measure	Base size Q_B	Base cost C_B (\$)	Size range	Cost exponent M
Agitated reactor	CS	Volume (m^3)	1	1.15×10^4	1–50	0.45
Pressure vessel	SS	Mass (t)	6	9.84×10^4	6–100	0.82
Distillation column (Empty shell)	CS	Mass (t)	8	6.56×10^4	8–300	0.89
Sieve trays (10 trays)	CS	Column diameter (m)	0.5	6.56×10^3	0.5–4.0	0.91
Valve trays (10 trays)	CS	Column diameter (m)	0.5	1.80×10^4	0.5–4.0	0.97
Structured packing (5 m height)	SS (low grade)	Column diameter (m)	0.5	1.80×10^4	0.5–4.0	1.70
Scrubber (Including random packing)	SS (low grade)	Volume (m^3)	0.1	4.92×10^3	0.1–20	0.53
Cyclone	CS	Diameter (m)	0.4	1.64×10^3	0.4–3.0	1.20
Vacuum filter	CS	Filter area (m^2)	10	8.36×10^4	10–25	0.49
Dryer	SS (low grade)	Evaporation rate (kg $H_2O \cdot h^{-1}$)	700	2.30×10^5	700–3000	0.65
Shell-and-tube heat exchanger	CS	Heat transfer area (m^2)	80	3.28×10^4	80–4000	0.68
Air-cooled heat exchanger	CS	Plain tube heat transfer area (m^2)	200	1.56×10^5	200–2000	0.89
Centrifugal pump (Small, including motor)	SS (high grade)	Power (kW)	1	1.97×10^3	1–10	0.35
Centrifugal pump (Large, including motor)	CS	Power (kW)	4	9.84×10^3	4–700	0.55
Compressor (Including motor)		Power (kW)	250	9.84×10^4	250–10,000	0.46
Fan (Including motor)	CS	Power (kW)	50	1.23×10^4	50–200	0.76
Vacuum pump (Including motor)	CS	Power (kW)	10	1.10×10^4	10–45	0.44
Electric motor		Power (kW)	10	1.48×10^3	10–150	0.85
Storage tank (Small atmospheric)	SS (low grade)	Volume (m^3)	0.1	3.28×10^3	0.1–20	0.57
Storage tank (Large atmospheric)	CS	Volume (m^3)	5	1.15×10^4	5–200	0.53
Silo	CS	Volume (m^3)	60	1.72×10^4	60–150	0.70
Package steam boiler (Fire-tube boiler)	CS	Steam generation ($kg \cdot h^{-1}$)	50,000	4.64×10^5	50,000–350,000	0.96
Field erected steam boiler (Water-tube boiler)	CS	Steam generation ($kg \cdot h^{-1}$)	20,000	3.28×10^5	10,000–800,000	0.81
Cooling tower (Forced draft)		Water flowrate ($m^3 \cdot h^{-1}$)	10	4.43×10^3	10–40	0.63

CS = carbon steel; SS (low grade) = low-grade stainless steel, for example, type 304; SS (high grade) = high-grade stainless steel, for example, type 316 magazine and the Nelson–Farrar Cost Indexes for refinery construction (1946 index = 100) published in the *Oil and Gas Journal*. The Chemical Engineering (CE) Indexes are particularly useful. CE Indexes are available for equipment covering:

- Heat Exchangers and Tanks
- Pipes, Valves and Fittings
- Process Instruments
- Pumps and Compressors
- Electrical Equipment
- Structural Supports and Miscellaneous.

A combined CE Index of Equipment is available. CE Indexes are also available for:

- Construction and Labor Index
- Buildings Index
- Engineering and Supervision Index.

All of the above indexes are combined to produce a CE Composite Index.

Table 2.1 presents data for a number of equipment items on the basis of January 2000 costs[7] (CE Composite Index = 391.1, CE Index of Equipment = 435.8).

Cost correlations for vessels are normally expressed in terms of the mass of the vessel. This means that not only a preliminary sizing of the vessel is required but also a preliminary assessment of the mechanical design[9,10].

Materials of construction have a significant influence on the capital cost of equipment. Table 2.2 gives some approximate average factors to relate the different materials of construction for equipment capital cost.

It should be emphasized that the factors in Table 2.2 are average and only approximate and will vary, amongst other things, according to the type of equipment. As an example, consider the effect of materials of construction on the capital cost of distillation columns. Table 2.3 gives materials of construction cost factors for distillation columns.

The cost factors for shell-and-tube heat exchangers are made more complex by the ability to construct the different components from different materials of construction. Table 2.4 gives typical materials of construction factors for shell-and-tube heat exchangers.

Table 2.2 Typical average equipment materials of construction capital cost factors.

Material	Correction factor f_M
Carbon steel	1.0
Aluminum	1.3
Stainless steel (low grades)	2.4
Stainless steel (high grades)	3.4
Hastelloy C	3.6
Monel	4.1
Nickel and inconel	4.4
Titanium	5.8

Table 2.3 Typical materials of construction capital cost factors for pressure vessels and distillation columns[9,10].

Material	Correction factor f_M
Carbon steel	1.0
Stainless steel (low grades)	2.1
Stainless steel (high grades)	3.2
Monel	3.6
Inconel	3.9
Nickel	5.4
Titanium	7.7

Table 2.4 Typical materials of construction capital cost factors for shell-and-tube heat exchangers[2].

Material	Correction factor f_M
CS shell and tubes	1.0
CS shell, aluminum tubes	1.3
CS shell, monel tubes	2.1
CS shell, SS (low grade) tubes	1.7
SS (low grade) shell and tubes	2.9

Its operating pressure also influences equipment capital cost as a result of thicker vessel walls to withstand increased pressure. Table 2.5 presents typical factors to account for the pressure rating.

As with materials of construction correction factors, the pressure correction factors in Table 2.5 are average and only approximate and will vary, amongst other things, according to the type of equipment. Finally, its operating temperature also influences equipment capital cost. This is caused by, amongst other factors, a decrease in the allowable stress for materials of construction as the temperature increases. Table 2.6 presents typical factors to account for the operating temperature.

Thus, for a base cost for carbon steel equipment at moderate pressure and temperature, the actual cost can be

Table 2.5 Typical equipment pressure capital cost factors.

Design pressure (bar absolute)	Correction factor f_P
0.01	2.0
0.1	1.3
0.5 to 7	1.0
50	1.5
100	1.9

Table 2.6 Typical equipment temperature capital cost factors.

Design temperature (°C)	Correction factor f_T
0–100	1.0
300	1.6
500	2.1

estimated from:

$$C_E = C_B \left(\frac{Q}{Q_B} \right)^M f_M f_P f_T \qquad (2.3)$$

where C_E = equipment cost for carbon steel at moderate pressure and temperature with capacity Q

C_B = known base cost for equipment with capacity Q_B

M = constant depending on equipment type

f_M = correction factor for materials of construction

f_P = correction factor for design pressure

f_T = correction factor for design temperature

In addition to the purchased cost of the equipment, investment is required to install the equipment. Installation costs include:

- cost of installation
- piping and valves
- control systems
- foundations
- structures
- insulation
- fire proofing
- electrical
- painting
- engineering fees
- contingency.

The total capital cost of the installed battery limits equipment will normally be two to four times the purchased cost of the equipment[11,12].

In addition to the investment within the battery limits, investment is also required for the structures, equipment and services outside of the battery limits that are required to make the process function.

2. *Utility investment*: Capital investment in utility plant could include equipment for:

- electricity generation
- electricity distribution
- steam generation
- steam distribution
- process water
- cooling water
- firewater
- effluent treatment
- refrigeration
- compressed air
- inert gas (nitrogen).

The cost of utilities is considered from their sources within the site to the battery limits of the chemical process served.

3. *Off-site investment*: Off-site investment includes

- auxiliary buildings such as offices, medical, personnel, locker rooms, guardhouses, warehouses and maintenance shops
- roads and paths
- railroads
- fire protection systems
- communication systems
- waste disposal systems
- storage facilities for end product, water and fuel not directly connected with the process
- plant service vehicles, loading and weighing devices.

The cost of the utilities and off-sites (together sometimes referred to as *services*) ranges typically from 20 to 40% of the total installed cost of the battery limits plant[13]. In general terms, the larger the plant, the larger will tend to be the fraction of the total project cost that goes to utilities and off-sites. In other words, a small project will require typically 20% of the total installed cost for utilities and off-sites. For a large project, the figure can be typically up to 40%.

4. *Working capital*: Working capital is what must be invested to get the plant into productive operation. This is money invested before there is a product to sell and includes:

- raw materials for plant start-up (including wasted raw materials)
- raw materials, intermediate and product inventories
- cost of transportation of materials for start-up
- money to carry accounts receivable (i.e. credit extended to customers) less accounts payable (i.e. credit extended by suppliers)
- money to meet payroll when starting up.

Theoretically, in contrast to fixed investment, this money is not lost but can be recovered when the plant is closed down.

Stocks of raw materials, intermediate and product inventories often have a key influence on the working capital and are under the influence of the designer. Issues relating to storage will be discussed in more detail in

Chapters 13 and 14. For an estimate of the working capital requirements, take either[14]:

(a) 30% of annual sales, or
(b) 15% of total capital investment.

5. *Total capital cost*: The total capital cost of the process, services and working capital can be obtained by applying multiplying factors or *installation factors* to the purchase cost of individual items of equipment[11,12]:

$$C_F = \sum_i f_i C_{E,i} \tag{2.4}$$

where C_F = fixed capital cost for the complete system
$C_{E,i}$ = cost of Equipment i
f_i = installation factor for Equipment i

If an average installation factor for all types of equipment is to be used[11],

$$C_F = f_I \sum_i C_{E,i} \tag{2.5}$$

where f_I = overall installation factor for the complete system.

The overall installation factor for new design is broken down in Table 2.7 into component parts according to the dominant phase being processed. The cost of the installation will depend on the balance of gas and liquid processing versus solids processing. If the plant handles only gases and liquids, it can be characterized as fluid processing. A plant can be characterized as solids processing if the bulk of the material handling is solid phase. For example, a solid processing plant could be a coal or an ore preparation plant. Between the two extremes of fluid processing and solids processing are processes that handle a significant amount of both solids and fluids. For example, a shale oil plant involves preparation of the shale oil followed by extraction of fluids from the shale oil and then separation and processing of the fluids. For these types of plant, the contributions to the capital cost can be estimated from the two extreme values in Table 2.7 by interpolation in proportion of the ratio of major processing steps that can be characterized as fluid processing and solid processing.

A number of points should be noted about the various contributions to the capital cost in Table 2.7. The values are:

- based on carbon steel, moderate operating pressure and temperature
- average values for all types of equipment, whereas in practice the values will vary according to the type of equipment
- only guidelines and the individual components will vary from project to project
- applicable to new design only.

Table 2.7 Typical factors for capital cost based on delivered equipment costs.

Item	Type of process	
	Fluid processing	Solid processing
Direct costs		
Equipment delivered cost	1	1
Equipment erection, f_{ER}	0.4	0.5
Piping (installed), f_{PIP}	0.7	0.2
Instrumentation & controls (installed), f_{INST}	0.2	0.1
Electrical (installed), f_{ELEC}	0.1	0.1
Utilities, f_{UTIL}	0.5	0.2
Off-sites, f_{OS}	0.2	0.2
Buildings (including services), f_{BUILD}	0.2	0.3
Site preparation, f_{SP}	0.1	0.1
Total capital cost of installed equipment	3.4	2.7
Indirect costs		
Design, engineering and construction, f_{DEC}	1.0	0.8
Contingency (about 10% of fixed capital costs), f_{CONT}	0.4	0.3
Total fixed capital cost	4.8	3.8
Working capital		
Working capital (15% of total capital cost), f_{WC}	0.7	0.6
Total capital cost, f_I	5.8	4.4

When equipment uses materials of construction other than carbon steel, or operating temperatures are extreme, the capital cost needs to be adjusted accordingly. Whilst the equipment cost and its associated pipework will be changed, the other installation costs will be largely unchanged, whether the equipment is manufactured from carbon steel or exotic materials of construction. Thus, the application of the factors from Tables 2.2 to 2.6 should only be applied to the equipment and pipework:

$$\begin{aligned} C_F = {} & \sum_i [f_M f_P f_T (1 + f_{PIP})]_i C_{E,i} \\ & + (f_{ER} + f_{INST} + f_{ELEC} + f_{UTIL} + f_{OS} + f_{BUILD} \\ & + f_{SP} + f_{DEC} + f_{CONT} + f_{WS}) \sum_i C_{E,i} \end{aligned} \tag{2.6}$$

Thus, to estimate the fixed capital cost:

1. list the main plant items and estimate their size;
2. estimate the equipment cost of the main plant items;

3. adjust the equipment costs to a common time basis using a cost index;
4. convert the cost of the main plant items to carbon steel, moderate pressure and moderate temperature;
5. select the appropriate installation subfactors from Table 2.7 and adjust for individual circumstances;
6. select the appropriate materials of construction, operating pressure and operating temperature correction factors for each of the main plant items;
7. apply Equation 2.6 to estimate the total fixed capital cost.

Equipment cost data used in the early stages of a design will by necessity normally be based on capacity, materials of construction, operating pressure and operating temperature. However, in reality, the equipment cost will depend also on a number of factors that are difficult to quantify[15]:

- multiple purchase discounts
- buyer–seller relationships
- capacity utilization in the fabrication shop (i.e. how busy the fabrication shop is)
- required delivery time
- availability of materials and fabrication labor
- special terms and conditions of purchase, and so on.

Care should also be taken to the geographic location. Costs to build the same plant can differ significantly between different locations, even within the same country. Such differences will result from variations in climate and its effect on the design requirements and construction conditions, transportation costs, local regulations, local taxes, availability and productivity of construction labor, and so on[16]. For example, in the United States of America, Gulf Coast costs tend to be the lowest, with costs in other areas typically 20 to 50% higher, and those in Alaska two or three times higher than US Gulf Coast[16]. In Australia, costs tend to be the lowest in the region of Sydney and the other metropolitan cities, with costs in remote areas such as North Queensland typically 40 to 80% higher[15]. Costs also differ from country to country. For example, relative to costs for a plant located in the US Gulf Coast, costs in India might be expected to be 20% cheaper, in Indonesia 30% cheaper, but in the United Kingdom 15% more expensive, because of labor costs, cost of land, and so on[15].

It should be emphasized that capital cost estimates using installation factors are at best crude and at worst highly misleading. When preparing such an estimate, the designer spends most of the time on the equipment costs, which represents typically 20 to 40% of the total installed cost. The bulk costs (civil engineering, labor, etc.) are factored costs that lack definition. At best, this type of estimate can be expected to be accurate to ±30%. To obtain greater accuracy requires detailed examination of all aspects of the investment. Thus, for example, to estimate the erection cost accurately requires knowledge of how much concrete will be used for foundations, how much structural steelwork is required, and so on. Such detail can only be included from access to a large database of cost information.

The shortcomings of capital cost estimates using installation factors are less serious in preliminary process design if used to compare options on a common basis. If used to compare options, the errors will tend to be less serious as the errors will tend to be consistent across the options.

Example 2.1 A new heat exchanger is to be installed as part of a large project. Preliminary sizing of the heat exchanger has estimated its heat transfer area to be 500 m^2. Its material of construction is low-grade stainless steel, and its pressure rating is 5 bar. Estimate the contribution of the heat exchanger to the total cost of the project (CE Index of Equipment = 441.9).

Solution From Equation 2.1 and Table 2.1, the capital cost of a carbon steel heat exchanger can be estimated from:

$$\begin{aligned} C_E &= C_B\left(\frac{Q}{Q_B}\right)^M \\ &= 3.28 \times 10^4 \left(\frac{500}{80}\right)^{0.68} \\ &= \$11.4 \times 10^4 \end{aligned}$$

The cost can be adjusted to bring it up-to-date using the ratio of cost indexes:

$$\begin{aligned} C_E &= 11.4 \times 10^4 \left(\frac{441.9}{435.8}\right) \\ &= \$11.6 \times 10^4 \end{aligned}$$

The cost of a carbon steel heat exchanger needs to be adjusted for the material of construction. Because of the low pressure rating, no correction for pressure is required (Table 2.5), but the cost needs to be adjusted for the material of construction. From Table 2.4, $f_M = 2.9$, and the total cost of the installed equipment can be estimated from Equation 2.6 and Table 2.7. If the project is a complete new plant, the contribution of the heat exchanger to the total cost can be estimated to be:

$$\begin{aligned} C_F &= f_M(1 + f_{PIP})C_E + (f_{ER} + f_{INST} + f_{ELEC} + f_{UTIL} \\ &\quad + f_{OS} + f_{BUILD} + f_{SP} + f_{DEC} + f_{CONT} + f_{WS})C_E \\ &= 2.9(1 + 0.7)11.6 \times 10^4 + (0.4 + 0.2 + 0.1 + 0.5 \\ &\quad + 0.2 + 0.2 + 0.1 + 1.0 + 0.4 + 0.7)11.6 \times 10^4 \\ &= 8.73 \times 11.6 \times 10^4 \\ &= \$1.01 \times 10^6 \end{aligned}$$

Had the new heat exchanger been an addition to an existing plant that did not require investment in electrical services, utilities, off-sites, buildings, site preparation or working capital, then the cost would be estimated from:

$$\begin{aligned} C_F &= f_M(1 + f_{PIP})C_E + (f_{ER} + f_{INST} + f_{DEC} + f_{CONT})C_E \\ &= 2.9(1 + 0.7)11.6 \times 10^4 + (0.4 + 0.2 + 1.0 + 0.4)11.6 \times 10^4 \\ &= 6.93 \times 11.6 \times 10^4 \\ &= \$8.04 \times 10^5 \end{aligned}$$

Installing a new heat exchanger into an existing plant might require additional costs over and above those estimated here. Connecting new equipment to existing equipment, modifying or relocating existing equipment to accommodate the new equipment and downtime might all add to the costs.

2.3 CAPITAL COST FOR RETROFIT

Estimating the capital cost of a retrofit project is much more difficult than for new design. In principle, the cost of individual items of new equipment will usually be the same, whether it is a grassroot design or a retrofit. However, in new design, multiple orders of equipment might lead to a reduction in capital cost from the equipment vendor and lower transportation costs. By contrast, installation factors for equipment in retrofit can be completely different from grassroot design, and could be higher or lower. If the new equipment can take advantage of existing space, foundations, electrical cabling, and so on, the installation factor might in some cases be lower than in new design. This will especially be the case for small items of equipment. However, most often, retrofit installation factors will tend to be higher than in grassroot design and can be very much higher. This is because existing equipment might need to be modified or moved to allow installation of new equipment. Also, access to the area where the installation is required is likely to be much more restricted in retrofit than in the phased installation of new plant. Smaller projects (as the retrofit is likely to be) tend to bring higher cost of installation per unit of installed equipment than larger projects.

As an example, one very common retrofit situation is the replacement of distillation column internals to improve the performance of the column. The improvement in performance sought is often an increase in the throughput. This calls for existing internals to be removed and then to be replaced with the new internals. Table 2.8 gives typical factors for the removal of old internals and the installation of new ones[17].

Table 2.8 Modification costs for distillation column retrofit[17].

Column modification	Cost of modification (multiply factor by cost of new hardware)
Removal of trays to install new trays	0.1 for the same tray spacing 0.2 for different tray spacing
Removal of trays to install packing	0.1
Removal of packing to install new trays	0.07
Installation of new trays	1.0–1.4 for the same tray spacing 1.2–1.5 for different tray spacing 1.3–1.6 when replacing packing
Installation of new structured packing	0.5–0.8

As far as utilities and off-sites are concerned, it is also difficult to generalize. Small retrofit projects are likely not to require any investment in utilities and off-sites. Larger-scale retrofit might demand a major revamp of the utilities and off-sites. Such a revamp of utilities and off-sites can be particularly expensive, because existing equipment might need to be modified or removed to make way for new utilities and off-sites equipment.

Working capital is also difficult to generalize. Most often, there will be no significant working capital associated with a retrofit project. For example, if a few items of equipment are replaced to increase the capacity of a plant, this will not significantly change the raw materials and product inventories, money to carry accounts receivable, money to meet payroll, and so on. On the other hand, if the plant changes function completely, significant new storage capacity is added, and so on, there might be a significant element of working capital.

One of the biggest sources of cost associated with retrofit can be the *downtime* (the period during which the plant will not be productive) required to carry out the modifications. The cost of lost production can be the dominant feature of retrofit projects. The cost of lost production should be added to the capital cost of a retrofit project. To minimize the downtime and cost of lost production requires that as much preparation as possible is carried out whilst the plant is operating. The modifications requiring the plant to be shut down should be minimized. For example, it might be possible for new foundations to be installed and new equipment put into place while the plant is still operating, leaving the final pipework and electrical modifications for the shutdown. Retrofit projects are often arranged such that the preparation is carried out prior to a regular maintenance shutdown, with the final modifications coinciding with the planned maintenance shutdown. Such considerations often dominate the decisions made as to how to modify the process for retrofit.

Because of all of these uncertainties, it is difficult to provide general guidelines for capital cost of retrofit projects. The basis of the capital cost estimate should be to start with the required investment in new equipment. Installation factors for the installation of equipment for grassroot design from Table 2.7 need to be adjusted according to circumstances (usually increased). If old equipment needs to be modified to take up a new role (e.g. move an existing heat exchanger to a new duty), then an installation cost must be applied without the equipment cost. In the absence of better information, the installation cost can be taken to be that for the equivalent piece of new equipment. Some elements of the total cost breakdown in Table 2.7 will not be relevant and should not be included. In general, for the estimation of capital cost for retrofit, a detailed examination of the individual features of retrofit projects is necessary.

Example 2.2 An existing heat exchanger is to be repiped to a new duty in a retrofit project without moving its location. The only significant investment is piping modifications. The heat transfer area of the existing heat exchanger is 500 m^2. The material of construction is low-grade stainless steel, and its design pressure is 5 bar. Estimate the cost of the project (CE Index of Equipment = 441.9).

Solution All retrofit projects have individual characteristics, and it is impossible to generalize the costs. The only way to estimate costs with any certainty is to analyze the costs of all of the modifications in detail. However, in the absence of such detail, a very preliminary estimate can be obtained by estimating the retrofit costs from the appropriate installation costs for a new design. In this case, piping costs can be estimated from those for a new heat exchanger of the same specification, but excluding the equipment cost. For Example 2.1, the cost of a new stainless steel heat exchanger with an area of 500 m^2 was estimated to be $\$11.6 \times 10^4$. The piping costs (stainless steel) can therefore be estimated to be:

$$\begin{aligned}\text{Piping cost} &= f_M f_{PIP} C_E \\ &= 2.9 \times 0.7 \times 11.6 \times 10^4 \\ &= 2.03 \times 11.6 \times 10^4 \\ &= \$2.35 \times 10^5\end{aligned}$$

This estimate should not be treated with any confidence. It will give an idea of the costs and might be used to compare retrofit options on a like-for-like basis, but could be very misleading.

Example 2.3 An existing distillation column is to be revamped to increase its capacity by replacing the existing sieve trays with stainless steel structured packing. The column shell is 46 m tall and 1.5 m diameter and currently fitted with 70 sieve trays with a spacing of 0.61 m. The existing trays are to be replaced with stainless steel structured packing with a total height of 30 m. Estimate the cost of the project (CE Index of Equipment = 441.9).

Solution First, estimate the purchase cost of the new structured packing from Equation 2.1 and Table 2.1, which gives costs for a 5-m height of packing:

$$\begin{aligned}C_E &= C_B\left(\frac{Q}{Q_B}\right)^M \\ &= 1.8 \times 10^4 \times \frac{30}{5}\left(\frac{1.5}{0.5}\right)^{1.7} \\ &= \$6.99 \times 10^5\end{aligned}$$

Adjusting the cost to bring it up-to-date using the ratio of cost indexes:

$$\begin{aligned}C_E &= 6.99 \times 10^5\left(\frac{441.9}{435.8}\right) \\ &= \$7.09 \times 10^5\end{aligned}$$

From Table 2.8, the factor for removing the existing trays is 0.1 and that for installing the new packing is 0.5 to 0.8 (say 0.7).

Estimated total cost of the project:

$$\begin{aligned}&= (1 + 0.1 + 0.7)7.09 \times 10^5 \\ &= \$1.28 \times 10^6\end{aligned}$$

2.4 ANNUALIZED CAPITAL COST

Capital for new installations may be obtained from:

a. Loans from banks
b. Issue by the company of common (ordinary) stock, preferred stock or bonds (debenture stock)
c. Accumulated net cash flow arising from company profit over time.

Interest on loans from banks, preferred stock and bonds is paid at a fixed rate of interest. A share of the profit of the company is paid as a dividend on common stock and preferred stock (in addition to the interest paid on preferred stock).

The cost of the capital for a project thus depends on its source. The source of the capital often will not be known during the early stages of a project, and yet there is a need to select between process options and carry out optimization on the basis of both capital and operating costs. This is difficult to do unless both capital and operating costs can be expressed on a common basis. Capital costs can be expressed on an annual basis if it is assumed that the capital has been borrowed over a fixed period (usually 5 to 10 years) at a fixed rate of interest, in which case the capital cost can be annualized according to

$$\text{Annualized capital cost} = \text{capital cost} \times \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2.7}$$

where i = fractional interest rate per year
n = number of years

The derivation of Equation 2.7 is given in Appendix A.

As stated previously, the source of capital is often not known, and hence it is not known whether Equation 2.7 is appropriate to represent the cost of capital. Equation 2.7 is, strictly speaking, only appropriate if the money for capital expenditure is to be borrowed over a fixed period at a fixed rate of interest. Moreover, if Equation 2.7 is accepted, then the number of years over which the capital is to be annualized is known, as is the rate of interest. However, the most important thing is that, even if the source of capital is not known, and uncertain assumptions are necessary, Equation 2.7 provides a common basis for the comparison of competing projects and design alternatives within a project.

Example 2.4 The purchased cost of a new distillation column installation is \$1 million. Calculate the annual cost of installed capital if the capital is to be annualized over a five-year period at a fixed rate of interest of 5%.

Solution First, calculate the installed capital cost:

$$
\begin{aligned}
C_F &= f_i C_E \\
&= 5.8 \times (1{,}000{,}000) \\
&= \$5{,}800{,}000 \\
\text{Annualization factor} &= \frac{i(1+i)^n}{(1+i)^n - 1} \\
&= \frac{0.05(1+0.05)^5}{(1+0.05)^5 - 1} = 0.2310 \\
\text{Annualized capital cost} &= 5,800,000 \times 0.2310 \\
&= \$1{,}340{,}000\ \text{y}^{-1}
\end{aligned}
$$

When using annualized capital cost to carry out optimization, the designer should not lose sight of the uncertainties involved in the capital annualization. In particular, changing the annualization period can lead to very different results when, for example, carrying out a trade-off between energy and capital costs. When carrying out optimization, the sensitivity of the result to changes in the assumptions should be tested.

2.5 OPERATING COST

1. *Raw materials cost*: In most processes, the largest individual operating cost is raw materials. The cost of raw materials and the product selling prices tend to have the largest influence on the economic performance of the process. The cost of raw materials and price of products depends on whether the materials in question are being bought and sold under a contractual arrangement (either within or outside the company) or on the open market. Open market prices for some chemical products can fluctuate considerably with time. Raw materials might be purchased and products sold below or above the open market price when under a contractual arrangement, depending on the state of the market. Buying and selling on the open market may give the best purchase and selling prices but give rise to an uncertain economic environment. A long-term contractual agreement may reduce profit per unit of production but gives a degree of certainty over the project life.

The values of raw materials and products can be found in trade journals such as Chemical Marketing Reporter (published by Schnell Publishing Company), European Chemical News and Asian Chemical News (published by Reed Business Information). However, the values reported in such sources will be subject to short-term fluctuations, and long-term forecasts will be required for investment analysis.

2. *Catalysts and chemicals consumed in manufacturing other than raw materials*: Catalysts will need to be replaced or regenerated though the life of a process (see Chapter 7). The replacement of catalysts might be on a continuous basis if homogeneous catalysts are used (see Chapters 5 and 7). Heterogeneous catalysts might also be replaced continuously if they deteriorate rapidly, and regeneration cannot fully reinstate the catalyst activity. More often for heterogeneous catalysts, regeneration or replacement will be carried out on an intermittent basis, depending on the characteristics of the catalyst deactivation.

In addition to the cost of catalysts, there might be significant costs associated with chemicals consumed in manufacturing that do not form part of the final product. For example, acids and alkalis might be consumed to adjust the pH of streams. Such costs might be significant.

3. *Utility operating cost*: Utility operating cost is usually the most significant variable operating cost after the cost of raw materials. This is especially the case for the production of commodity chemicals. Utility operating cost includes:

- fuel
- electricity
- steam
- cooling water
- refrigeration
- compressed air
- inert gas.

Utility costs can vary enormously between different processing sites. This is especially true of fuel and power costs. Not only do fuel costs vary considerably between different fuels (coal, oil, natural gas) but costs also tend to be sensitive to market fluctuations. Contractual relationships also have a significant effect on fuel costs. The price paid for fuel depends very much on how much is purchased and the pattern of usage.

When electricity is bought from centralized power-generation companies under long-term contract, the price tends to be more stable than fuel costs, since power-generation companies tend to negotiate long-term contracts for fuel supply. However, purchased electricity prices (and sales price if excess electricity is generated and exported) are normally subject to tariff variations. Electricity tariffs can depend on the season of the year (winter versus summer), the time of day (night versus day) and the time of the week (weekend versus weekday). In hot countries, electricity is usually more expensive in the summer than in the winter because of the demand from air conditioning systems. In cold countries, electricity is usually more expensive in the winter than in the summer because of the demand from space heating. The price structure for electricity can be complex, but should be predictable if based on contractual arrangements. If electricity is purchased from a spot market in those countries that have such arrangements, then prices can vary wildly.

Steam costs vary with the price of fuel and electricity. If steam is only generated at low pressure and not used for power generation in steam turbines, then the cost can be estimated from fuel costs assuming an efficiency of generation and distribution losses. The efficiency of generation depends on the boiler efficiency and the steam consumed in boiler feedwater production (see Chapter 23). Losses from the steam distribution system include heat losses from steam distribution and condensate return pipework to the environment, steam condensate lost to drain and not returned to the boilers and steam leaks. The efficiency of steam generation (including auxiliary boiler-house requirements, see Chapter 23) is typically around 85 to 90% and distribution losses of perhaps another 10%, giving an overall efficiency for steam generation and distribution of typically around 75 to 80% (based on the net calorific value of the fuel). Care should be exercised when considering boiler efficiency and the efficiency of steam generation. These figures are most often quoted on the basis of *gross calorific value* of the fuel, which includes the latent heat of the water vapor from combustion. This latent heat is rarely recovered through condensation of the water vapor in the combustion gases. The *net calorific value* of the fuel assumes that the latent heat of the water vapor is not recovered and is therefore the most relevant value. Yet, figures are most often quoted on the basis of gross calorific value.

If high-pressure steam mains are used, then the cost of steam should be related in some way to its capacity to generate power in a steam turbine rather than simply to its additional heating value. The high-pressure steam is generated in the utility boilers, and the low-pressure steam is generated by reducing pressure through steam turbines to produce power. This will be discussed in more detail in Chapter 23. One simple way to cost steam is to calculate the cost of the fuel required to generate the high-pressure steam (including any losses), and this fuel cost is then the cost of the high-pressure steam. Low-pressure mains have a value equal to that of the high-pressure mains minus the value of power generated by letting the steam down to the low pressure in a steam turbine. To calculate the cost of steam that has been expanded though a steam turbine, the power generated in such an expansion must be calculated. The simplest way to do this is on the basis of a comparison between an ideal and a real expansion though a steam turbine. Figure 2.1 shows a steam turbine expansion on an enthalpy-entropy plot. In an ideal turbine, steam with an initial pressure P_1 and enthalpy H_1 expands isentropically to pressure P_2 and enthalpy H_2. In such circumstances, the ideal work output is $(H_1 - H_2)$. Because of the frictional effects in the turbine nozzles and blade passages, the exit enthalpy is greater than it would be in an ideal turbine, and the work output is consequently less, given by H_2' in Figure 2.1. The actual work output is given by $(H_1 - H_2')$. The turbine isentropic efficiency η_{IS} measures the ratio of the actual to ideal work obtained:

$$\eta_{IS} = \frac{H_1 - H_2'}{H_1 - H_2} \tag{2.8}$$

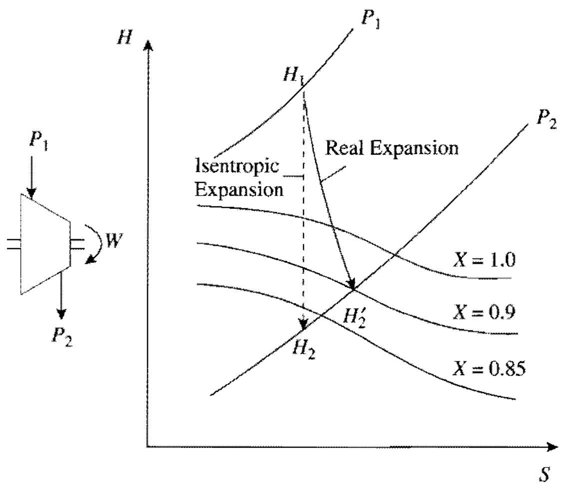

Figure 2.1 Steam turbine expansion.

The output from the turbine might be superheated or partially condensed, as is the case in Figure 2.1. The following example illustrates the approach.

Example 2.5 The pressures of three steam mains have been set to the conditions given in Table 2.9. High-pressure (HP) steam is generated in boilers at 41 barg and superheated to 400°C. Medium-pressure (MP) and low-pressure (LP) steam are generated by expanding high-pressure steam through a steam turbine with an isentropic efficiency of 80%. The cost of fuel is $4.00 GJ^{-1}, and the cost of electricity is $0.07 kW^{-1}·h^{-1}. Boiler feedwater is available at 100°C with a heat capacity of 4.2 kJ·kg^{-1}·K^{-1}. Assuming an efficiency of steam generation of 85% and distribution losses of 10%, estimate the cost of steam for the three levels.

Table 2.9 Steam mains pressure settings.

Mains	Pressure (barg)
HP	41
MP	10
LP	3

Solution *Cost of 41 barg steam.* From steam tables, for 41 barg steam at 400°C:

$$\text{Enthalpy} = 3212 \text{ kJ·kg}^{-1}$$

For boiler feedwater:

$$\begin{aligned}\text{Enthalpy} &= 4.2(100 - 0)(\text{relative to water at } 0^\circ\text{C}) \\ &= 420 \text{ kJ·kg}^{-1}\end{aligned}$$

To generate 41 barg steam at 400°C:

$$\text{Heat duty} = 3212 - 420 = 2792 \text{ kJ·kg}^{-1}$$

For 41 barg steam:

$$\begin{aligned} \text{Cost} &= 4.00 \times 10^{-6} \times 2792 \times \frac{1}{0.75} \\ &= \$0.01489\ \text{kg}^{-1} \\ &= \$14.89\ \text{t}^{-1} \end{aligned}$$

Cost of 10 barg steam. Here 41 barg steam is now expanded to 10 barg in a steam turbine. From steam tables, inlet conditions at 41 barg and 400°C are:

$$\begin{aligned} H_1 &= 3212\ \text{kJ·kg}^{-1} \\ S_1 &= 6.747\ \text{kJ·kg}^{-1}\text{·K}^{-1} \end{aligned}$$

Turbine outlet conditions for isentropic expansion to 10 barg are:

$$\begin{aligned} H_2 &= 2873\ \text{kJ·kg}^{-1} \\ S_2 &= 6.747\ \text{kJ·kg}^{-1}\text{·K}^{-1} \end{aligned}$$

For single-stage expansion with isentropic efficiency of 80%:

$$\begin{aligned} H_2' &= H_1 - \eta_I(H_1 - H_2) \\ &= 3212 - 0.8(3212 - 2873) \\ &= 2941\ \text{kJ·kg}^{-1} \end{aligned}$$

From steam tables, the outlet temperature is 251°C, which corresponds to a superheat of 67°C. Although steam for process heating is preferred at saturated conditions, it is not desirable in this case to de-superheat by boiler feedwater injection to bring to saturation conditions. If saturated steam is fed to the main, then the heat losses from the main will cause a large amount of condensation in the main, which is undesirable. Hence, it is standard practice to feed steam to the main with a superheat of at least 10°C to avoid condensation in the main.

$$\begin{aligned} \text{Power generation} &= 3212 - 2941 \\ &= 271\ \text{kJ·kg}^{-1} \\ \text{Value of power generation} &= 271 \times \frac{0.07}{3600} \\ &= \$0.00527\ \text{kg}^{-1} \\ \text{Cost of 10 barg steam} &= 0.01489 - 0.00527 \\ &= \$0.00962\ \text{kg}^{-1} \\ &= \$9.62\ \text{t}^{-1} \end{aligned}$$

Cost of 3 barg steam. Here, 10 barg steam from the exit of the first turbine is assumed to be expanded to 3 barg in another turbine.

From steam tables, inlet conditions of 10 barg and 251°C are:

$$\begin{aligned} H_1 &= 2941\ \text{kJ·kg}^{-1} \\ S_1 &= 6.880\ \text{kJ·kg}^{-1}\text{·K}^{-1} \end{aligned}$$

Turbine outlet conditions for isentropic expansion to 3 barg are:

$$\begin{aligned} H_2 &= 2732\ \text{kJ·kg}^{-1} \\ S_2 &= 6.880\ \text{kJ·kg}^{-1}\text{·K}^{-1} \end{aligned}$$

For a single-stage expansion with isentropic efficiency of 80%

$$\begin{aligned} H_2' &= H_1 - \eta_{IS}(H_1 - H_2) \\ &= 2941 - 0.8(2941 - 2732) \\ &= 2774\ \text{kJ·kg}^{-1} \end{aligned}$$

From steam tables, the outlet temperature is 160°C, which is superheated by 16°C. Again, it is desirable to have some superheat for the steam fed to the low-pressure main.

Power generation

$$\begin{aligned} &= 2941 - 2774 \\ &= 167\ \text{kJ·kg}^{-1} \end{aligned}$$

Value of power generation

$$\begin{aligned} &= 167 \times \frac{0.07}{3600} \\ &= \$0.00325\ \text{kg}^{-1} \end{aligned}$$

Cost of 3 barg steam

$$\begin{aligned} &= 0.00962 - 0.00325 \\ &= \$0.00637\ \text{kg}^{-1} \\ &= \$6.37\ \text{t}^{-1} \end{aligned}$$

If the steam generated in the boilers is at a very high pressure and/or the ratio of power to fuel costs is high, then the value of low-pressure steam can be extremely low or even negative.

This simplistic approach to costing steam is often unsatisfactory, especially if the utility system already exists. Steam costs will be considered in more detail in Chapter 23.

The operating cost for cooling water tends to be low relative to the value of both fuel and electricity. The principal operating cost associated with the provision of cooling water is the cost of power to drive the cooling tower fans and cooling water circulation pumps. The cost of cooling duty provided by cooling water is in the order of 1% that of the cost of power. For example, if power costs $\$0.07\ \text{kW}^{-1}\text{·h}^{-1}$, then cooling water will typically cost $0.07 \times 0.01/3600 = \$0.19 \times 10^{-6}\ \text{kJ}^{-1}$ or $\$0.19\ \text{GJ}^{-1}$. Cooling water systems will be discussed in more detail in Chapter 24.

The cost of power required for a refrigeration system can be estimated as a multiple of the power required for an ideal system:

$$\frac{W_{IDEAL}}{Q_C} = \frac{T_H - T_C}{T_C} \tag{2.9}$$

where W_{IDEAL} = ideal power required for the refrigeration cycle

Q_C = the cooling duty

T_C = temperature at which heat is taken into the refrigeration cycle (K)

T_H = temperature at which heat is rejected from the refrigeration cycle (K)

The ratio of ideal to actual power is often around 0.6. Thus

$$W = \frac{Q_C}{0.6}\left(\frac{T_H - T_C}{T_C}\right) \qquad (2.10)$$

where W is the actual power required for the refrigeration cycle.

Example 2.6 A process requires 0.5 MW of cooling at −20°C. A refrigeration cycle is required to remove this heat and reject it to cooling water supplied at 25°C and returned at 30°C. Assuming a minimum temperature difference (ΔT_{min}) of 5°C and both vaporization and condensation of the refrigerant occur isothermally, estimate the annual operating cost of refrigeration for an electrically driven system operating 8000 hours per year. The cost of electricity is $0.07 kW$^{-1}\cdot$h^{-1}.

Solution

$$\begin{aligned}
W &= \frac{Q_C}{0.6}\left(\frac{T_H - T_C}{T_C}\right)\\
T_H &= 30 + 5 = 35^\circ\text{C} = 308\ \text{K}\\
T_C &= -20 - 5 = -25^\circ\text{C} = 248\ \text{K}\\
W &= \frac{0.5}{0.6}\left(\frac{308 - 248}{248}\right)\\
&= 0.202\ \text{MW}\\
\text{Cost of electricity} &= 0.202 \times 10^3 \times 0.07 \times 8{,}000\\
&= \$113,120\ \text{y}^{-1}
\end{aligned}$$

More accurate methods to calculate refrigeration costs will be discussed in Chapter 24.

4. *Labor cost*: The cost of labor is difficult to estimate. It depends on whether the process is batch or continuous, the level of automation, the number of processing steps and the level of production. When synthesizing a process, it is usually only necessary to screen process options that have the same basic character (e.g. continuous), have the same level of automation, have a similar number of processing steps and the same level of production. In this case, labor costs will be common to all options and hence will not affect the comparison.

If, however, options are to be compared that are very different in nature, such as a comparison between batch and continuous operation, some allowance for the difference in the cost of labor must be made. Also, if the location of the plant has not been fixed, the differences in labor costs between different geographical locations can be important.

5. *Maintenance*: The cost of maintenance depends on whether processing materials are solids on the one hand or gas and liquid on the other. Handling solids tends to increase maintenance costs. Highly corrosive process fluids increase maintenance costs. Average maintenance costs tend to be around 6% of the fixed capital investment[8].

2.6 SIMPLE ECONOMIC CRITERIA

To evaluate design options and carry out process optimization, simple economic criteria are needed. Consider what happens to the revenue from product sales after the plant has been commissioned. The sales revenue must pay for both fixed costs that are independent of the rate of production and variable costs, which do depend on the rate of production. After this, taxes are deducted to leave the net profit.

Fixed costs independent of the rate of production include:

- Capital cost repayments
- Routine maintenance
- Overheads (e.g. safety services, laboratories, personnel facilities, administrative services)
- Quality control
- Local taxes
- Labor
- Insurance

Variable costs that depend on the rate of production include:

- Raw materials
- Catalysts and chemicals consumed in manufacturing (other than raw materials)
- Utilities (fuel, steam, electricity, cooling water, process water, compressed air, inert gases, etc.)
- Maintenance costs incurred by operation
- Royalties
- Transportation costs

There can be an element of maintenance that is a fixed and an element that is variable. Fixed maintenance costs cover routine maintenance such as statutory maintenance on safety equipment that must be carried out irrespective of the rate of production. Variable maintenance costs result from certain items of equipment needing more maintenance as the production rate increases. Also, the royalties that cover the cost of purchasing another company's process technology may have different bases. Royalties may be a variable cost, since they can sometimes be paid in proportion to the rate of production or sales revenue. Alternatively, the royalty might be a single-sum payment at the beginning of the project. In this case, the single-sum payment will become part of the project capital investment. As such, it will be included in the annual capital repayment, and this becomes part of the fixed cost.

Two simple economic criteria are useful in process design:

1. *Economic potential (EP)*:

$$EP = \text{value of products} - \text{fixed costs} - \text{variable costs} - \text{taxes} \qquad (2.11)$$

2. *Total annual cost (TAC)*:

$$TAC = \text{fixed costs} + \text{variable costs} + \text{taxes} \qquad (2.12)$$

When synthesizing a flowsheet, these criteria are applied at various stages when the picture is still incomplete. Hence, it is usually not possible to account for all the fixed and variable costs listed above during the early stages of a project. Also, there is little point in calculating taxes until a complete picture of operating costs and cash flows has been established.

The preceding definitions of economic potential and total annual cost can be simplified if it is accepted that they will be used to compare the relative merits of different structural options in the flowsheet and different settings of the operating parameters. Thus, items that will be common to the options being compared can be neglected.

2.7 PROJECT CASH FLOW AND ECONOMIC EVALUATION

As the design progresses, more information is accumulated. The best methods of assessing the profitability of alternatives are based on projections of the cash flows during the project life[18].

Figure 2.2 shows the cash flow pattern for a typical project. The cash flow is a cumulative cash flow. Consider Curve 1 in Figure 2.2. From the start of the project at Point A, cash is spent without any immediate return. The early stages of the project consist of development, design and other preliminary work, which causes the cumulative curve to dip to Point B. This is followed by the main phase of capital investment in buildings, plant and equipment, and the curve drops more steeply to Point C. Working capital is spent to commission the plant between Points C and D. Production starts at D, where revenue from sales begins. Initially, the rate of production is likely to be below design conditions until full production is achieved at E. At F, the cumulative cash flow is again zero. This is the project breakeven point. Toward the end of the projects life at G, the net rate of cash flow may decrease owing to, for example, increasing maintenance costs, a fall in the market price for the product, and so on.

Ultimately, the plant might be permanently shut down or given a major revamp. This marks the end of the project, H. If the plant is shut down, working capital is recovered, and there may be salvage value, which would create a final cash inflow at the end of the project.

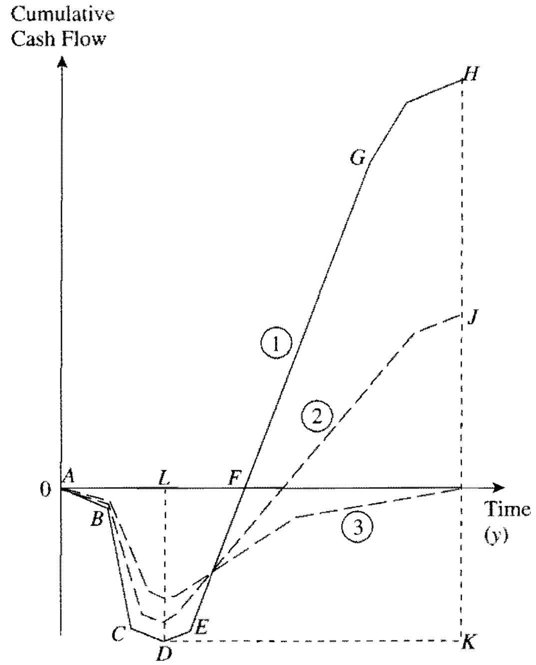

Figure 2.2 Cash flow pattern for a typical project. (From Allen DH, 1980, A Guide to the Economic Evaluation of Projects, IChemE, reproduced by permission of the Institution of Chemical Engineers.)

The predicted cumulative cash flow curve for a project throughout its life forms the basis for more detailed evaluation. Many quantitative measures or indices have been proposed. In each case, important features of the cumulative cash flow curve are identified and transformed into a single numerical measure as an index.

1. *Payback time*: Payback time is the time that elapses from the start of the project (A in Figure 2.2) to the breakeven point (F in Figure 2.2). The shorter the payback time, the more attractive is the project. Payback time is often calculated as the time to recoup the capital investment based on the mean annual cash flow. In retrofit, payback time is usually calculated as the time to recoup the retrofit capital investment from the mean annual improvement in operating costs.

2. *Return on Investment (ROI)*: Return on investment (ROI) is usually defined as the ratio of average yearly income over the productive life of the project to the total initial investment, expressed as a percentage. Thus, from Figure 2.2

$$ROI = \frac{KH}{KD} \times \frac{100}{LD} \%\text{per year} \qquad (2.13)$$

Payback and ROI select particular features of the project cumulative cash flow and ignore others. They take no account of the *pattern* of cash flow during a project.

The other indices to be described, net present value and discounted cash flow return, are more comprehensive because they take account of the changing pattern of project net cash flow with time. They also take account of the *time value* of money.

3. *Net present value (NPV)*: Since money can be invested to earn interest, money received now has a greater value than money if received at some time in the future. The net present value of a project is the sum of the present values of each individual cash flow. In this case, the *present* is taken to be the start of a project.

Time is taken into account by discounting the annual cash flow A_{CF} with the rate of interest to obtain the annual discounted cash flow A_{DCF}. Thus at the end of year 1

$$A_{DCF1} = \frac{A_{CF1}}{(1+i)}$$

at the end of year 2,

$$A_{DCF2} = \frac{A_{CF2}}{(1+i)^2}$$

and at the end of year n,

$$A_{DCFn} = \frac{A_{CFn}}{(1+i)^n} \qquad (2.14)$$

The sum of the annual discounted cash flows over n years ΣA_{DCF} is known as the *net present value* (NPV) of the project.

$$NPV = \sum A_{DCF} \qquad (2.15)$$

The value of NPV is directly dependent on the choice of the fractional interest rate i and project lifetime n.

Returning to the cumulative cash flow curve for a project, the effect of discounting is shown in Figure 2.2. Curve 1 is the original curve with no discounting, that is, $i = 0$, and the project NPV is equal to the final net cash position given by H. Curve 2 shows the effect of discounting at a fixed rate of interest, and the corresponding project NPV is given by J. Curve 3 in Figure 2.2 shows a larger rate of interest, but it is chosen such that the NPV is zero at the end of the project.

The greater the positive NPV for a project, the more economically attractive it is. A project with a negative NPV is not a profitable proposition.

4. *Discounted cash flow rate of return*: Discounted cash flow rate of return is defined as the discount rate i, which makes the NPV of a project to zero (Curve 3 in Figure 2.2):

$$NPV = \sum A_{DCF} = 0 \qquad (2.16)$$

The value of i given by this equation is known as the *discounted cash flow rate of return* (*DCFRR*). It may be found graphically or by trial and error.

Example 2.7 A company has the alternative of investing in one of two projects, A or B. The capital cost of both projects is $10 million. The predicted annual cash flows for both projects are shown in Table 2.10. Capital is restricted, and a choice is to be made on the basis of discounted cash flow rate of return, based on a five-year lifetime.

Table 2.10 Predicted annual cash flows.

	Cash flows ($\$10^6$)	
Year	Project A	Project B
0	−10	−10
1	1.6	6.5
2	2.8	5.2
3	4.0	4.0
4	5.2	2.8
5	6.4	1.6

Project *A*

Start with an initial guess for *DCFRR* of 20% and increase as detailed in Table 2.11.

Table 2.11 Calculation of *DCFRR* for Project *A*.

		DCF 20%		DCF 30%		DCF 25%	
Year	A_{CF}	A_{DCF}	ΣA_{DCF}	A_{DCF}	ΣA_{DCF}	A_{DCF}	ΣA_{DCF}
0	−10	−10	−10	−10	−10	−10	−10
1	1.6	1.33	−8.67	1.23	−8.77	1.28	−8.72
2	2.8	1.94	−6.73	1.66	−7.11	1.79	−6.93
3	4.0	2.31	−4.42	1.82	−5.29	2.05	−4.88
4	5.2	2.51	−1.91	1.82	−3.47	2.13	−2.75
5	6.4	2.57	0.66	1.72	−1.75	2.10	−0.65

Twenty percent is too low since ΣA_{DCF} is positive at the end of year 5. Thirty percent is too large since ΣA_{DCF} is negative at the end of year 5, as is the case with 25%. The answer must be between 20 and 25%. Interpolating on the basis of ΣA_{DCF} the $DCFRR \approx 23\%$.

Project *B*

Again, start with an initial guess for *DCFRR* of 20% and increase as detailed in Table 2.12.

From ΣA_{DCF} at the end of year 5, 20% is to low, 40% too high and 35% also too low. Interpolating on the basis of ΣA_{DCF}, the $DCFRR \approx 38\%$. Project B should therefore be chosen.

2.8 INVESTMENT CRITERIA

Economic analysis should be performed at all stages of an emerging project as more information and detail become available. The decision as to whether to proceed with a project will depend on many factors. There is most often

Table 2.12 Calculation of *DCFRR* for Project *B*.

		DCF 20%		DCF 40%		DCF 35%	
Year	A_{CF}	A_{DCF}	ΣA_{DCF}	A_{DCF}	ΣA_{DCF}	A_{DCF}	ΣA_{DCF}
0	−10	−10	−10	−10	−10	−10	−10
1	6.4	5.42	−4.58	4.64	−5.36	4.81	−5.19
2	5.2	3.61	−0.97	2.65	−2.71	2.85	−2.34
3	4.0	2.31	1.34	1.46	−1.25	1.63	−0.71
4	2.8	1.35	2.69	0.729	−0.521	0.843	0.133
5	1.6	0.643	3.33	0.297	−0.224	0.357	0.490

stiff competition within companies for any capital available for investment in projects. The decision as to where to spend the available capital on a particular project will, in the first instance but not exclusively, depend on the economic criteria discussed in the previous section. Criteria that account for the timing of the cash flows (the *NPV* and *DCFRR*) should be the basis of the decision-making. The higher the value of the *NPV* and *DCFRR* for a project, the more attractive it is. The absolute minimum acceptable value of the *DCFRR* is the market interest rate. If the *DCFRR* is lower than market interest rate, it would be better to put the money in the bank. For a *DCFRR* value greater than this, the project will show a profit, for a lesser value it will show a loss. The essential distinction between *NPV* and *DCFRR* is:

- *Net Present Value* measures profit but does not indicate how efficiently capital is being used.
- *DCFRR* measures how efficiently capital is being used but gives no indication of how large the profits will be.

If the goal is to maximize profit, *NPV* is the more important measure. If the supply of capital is restricted, which is usual, *DCFRR* can be used to decide which projects will use the capital most efficiently. Both measures are therefore important to characterize the economic value of a project.

Predicting future cash flows for a project is extremely difficult. There are many uncertainties, including the project life. Also, the appropriate interest rate will not be known with certainty. The acceptability of the rate of return will depend on the risks associated with the project and the company investment policy. For example, a *DCFRR* of 20% might be acceptable for a low risk project. A higher return of say 30% might be demanded of a project with some risk, whereas a high-risk project with significant uncertainty might demand a 50% *DCFRR*.

The sensitivity of the economic analysis to the underlying assumptions should always be tested. A sensitivity analysis should be carried out to test the sensitivity of the economic analysis to:

- errors in the capital cost estimate
- delays in the start-up of the project after the capital has been invested (particularly important for a high capital cost project)
- changes in the cost of raw materials
- changes in the sales price of the product
- reduction in the market demand for the product, and so on.

When carrying out an economic evaluation, the magnitude and timing of the cash flows, the project life and interest rate are not known with any certainty. However, providing that consistent assumptions are made for projections of cash flows and the assumed rate of interest, the economic analysis can be used to choose between competing projects. It is important to compare different projects and options within projects, on the basis of consistent assumptions. Thus, even though the evaluation will be uncertain in an absolute sense, it can still be meaningful in a relative sense for choosing between options. Because of this, it is important to have a reference against which to judge any project or option within a project.

However, the final decision to proceed with a project will be influenced as much by business strategy as by the economic measures described above. The business strategy might be to gradually withdraw from a particular market, perhaps because of adverse long-term projections of excessive competition, even though there might be short-term attractive investment opportunities. The long-term business strategy might be to move into different business areas, thereby creating investment priorities. Priority might be given to increasing market share in a particular product to establish business dominance in the area and achieve long-term global economies of scale in the business.

2.9 PROCESS ECONOMICS – SUMMARY

Process economics is required to evaluate design options, carry out process optimization and evaluate overall project profitability. Two simple criteria can be used:

- economic potential
- total annual cost.

These criteria can be used at various stages in the design without a complete picture of the process.

The dominant operating cost is usually raw materials. However, other significant operating costs involve catalysts and chemicals consumed other than raw materials, utility costs, labor costs and maintenance.

Capital costs can be estimated by applying installation factors to the purchase costs of individual items of equipment. However, there is considerable uncertainty associated with cost estimates obtained in this way, as equipment costs are typically only 20 to 40% of the total installed costs, with the remainder based on factors. Utility investment, off-site investment and working capital are also needed to complete the capital investment. The capital cost can be annualized by considering it as a loan over a fixed period at a fixed rate of interest.

As a more complete picture of the project emerges, the cash flows through the project life can be projected. This allows more detailed evaluation of project profitability on the basis of cash flows. Net present value can be used to measure the profit taking into account the time value of money. Discounted cash flow rate of return measures how efficiently the capital is being used.

Overall, there are always considerable uncertainties associated with an economic evaluation. In addition to the errors associated with the estimation of capital and operating costs, the project life or interest rates are not known with any certainty. The important thing is that different projects, and options within projects, are compared on the basis of consistent assumptions. Thus, even though the evaluation will be uncertain in an absolute sense, it will still be meaningful in a relative sense for choosing between options.

2.10 EXERCISES

1. The cost of a closed atmospheric cylindrical storage vessels can be considered to be proportional to the mass of steel required. Derive a simple expression for the dimensions of such a storage tank to give minimum capital cost. Assume the top and bottom are both flat.
2. A new agitated reactor with new external shell-and-tube heat exchanger and new centrifugal pump are to be installed in an existing facility. The agitated reactor is to be glass-lined, which can be assumed to have an equipment cost of three times the cost of a carbon steel vessel. The heat exchanger, pump and associated piping are all high-grade stainless steel. The equipment is rated for moderate pressure. The reactor has a volume of 9 m^3, the heat exchanger an area of 50 m^2 and the pump has a power of 5 KW. No significant investment is required in utilities, off-sites, buildings, site preparation or working capital. Using Equation 2.1 and Table 2.1 (extrapolating beyond the range of the correlation if necessary), estimate the cost of the project (CE Index of Equipment = 441.9).
3. Steam is distributed on a site via a high-pressure and low-pressure steam mains. The high-pressure mains is at 40 bar and 350°C. The low-pressure mains is at 4 bar. The high-pressure steam is generated in boilers. The overall efficiency of steam generation and distribution is 75%. The low-pressure steam is generated by expanding the high-pressure stream through steam turbines with an isentropic efficiency of 80%. The cost of fuel in the boilers is 3.5 $\$\cdot\text{GJ}^{-1}$, and the cost of electricity is \$0.05 $\text{KW}^{-1}\cdot\text{h}^{-1}$. The boiler feedwater is available at 100°C with a heat capacity of 4.2 $\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$. Estimate the cost of the high-pressure and low-pressure steam.
4. A refrigerated distillation condenser has a cooling duty of 0.75 MW. The condensing stream has a temperature of -10°C. The heat from a refrigeration circuit can be rejected to cooling water at a temperature of 30°C. Assuming a temperature difference in the distillation condenser of 5°C and a temperature difference for heat rejection from refrigeration to cooling water of 10°C, estimate the power requirements for the refrigeration.
5. Acetone is to be produced by the dehydrogenation of an aqueous solution of isopropanol according to the reaction:

$$\underset{\text{Isopropanol}}{(CH_3)_2CHOH} \longrightarrow \underset{\text{Acetone}}{CH_3COCH_3} + \underset{\text{Hydrogen}}{H_2}$$

The effluent from the reactor enters a phase separator that separates vapor from liquid. The liquid contains the bulk of the product, and the vapor is a waste stream. The vapor stream is at a temperature of 30°C and an absolute pressure of 1.1 bar. The component flowrates in the vapor stream are given in Table 2.13, together with their raw material values and fuel values. Three options are to be considered:

   a. Burn the vapor in a furnace
   b. Recover the acetone by absorption in water recycled from elsewhere in the process with the tail gas being burnt in a furnace. It is expected that 99% will be recovered by this method at a cost of 1.8 $\$\cdot\text{kmol}^{-1}$ acetone recovered.
   c. Recover the acetone by condensation using refrigerated coolant with the tail gas being burnt in a furnace. It is anticipated that a temperature of -10°C will need to be achieved in the condenser. It can be assumed that the hydrogen is an inert that will not dissolve in the liquid acetone. The vapor pressure of acetone is given by

$$\ln P = 10.031 - \frac{2940.5}{T - 35.93}$$

where P = pressure (bara)
T = absolute temperature (K)

The cost of refrigerant is \$11.5 GJ^{-1}, the mean molal heat capacity of the vapor is 40 $\text{kJ}\cdot\text{kmol}^{-1}\cdot\text{K}^{-1}$, and the latent heat of acetone is 29,100 $\text{kJ}\cdot\text{kmol}^{-1}$.

Calculate the economic potential of each option given the data in Table 2.13.

Table 2.13 Data for exercise 5.

Component	Flowrate in vapor ($\text{kmol}\cdot\text{h}^{-1}$)	Raw material value ($\$\cdot\text{kmol}^{-1}$)	Fuel value ($\$\cdot\text{kmol}^{-1}$)
Hydrogen	51.1	0	0.99
Acetone	13.5	34.8	6.85

6. A process for the production of cellulose acetate fiber produces a waste stream containing mainly air but with a small quantity of acetone vapor. The flowrate of air is 300 $\text{kmol}\cdot\text{h}^{-1}$ and that of acetone is 4.5 $\text{kmol}\cdot\text{h}^{-1}$. It is proposed to recover the acetone from the air by absorption into water followed by distillation of the acetone-water mixture. The absorber requires a flow of water 2.8 times that of the air.
   a. Assuming acetone costs 34.8 $\$\cdot\text{kmol}^{-1}$, process water costs \$0.004 kmol^{-1} and the process operates for 8000 $\text{h}\cdot\text{y}^{-1}$, calculate the maximum economic potential assuming complete recovery of the acetone.
   b. If the absorber and distillation column both operate at 99% recovery of acetone and the product acetone overhead from the distillation column must be 99% pure, sketch the flowsheet for the system and calculate the flows of acetone and water to and from the distillation column.

c. Calculate the revised economic potential to allow for incomplete recovery in the absorption and distillation columns. In addition, the effluent from the bottom of the distillation column will cost \$50 for each kmol of acetone plus \$0.004 for each kmol of water to treat before it can be disposed of to sewer.

7. A company has the option of investing in one of the two projects *A* or *B*. The capital cost of both projects is \$1,000,000. The predicted annual cash flows for both projects are shown in Table 2.14. For each project, calculate the:
   a. payback time for each project in terms of the average annual cash flow
   b. return on investment
   c. discounted cash flow rate of return

   What do you conclude from the result?

Table 2.14 Cash flows for two competing projects.

Year	Cash flows \$1000	
	Project *A*	Project *B*
0	−1000	−1000
1	150	500
2	250	450
3	350	300
4	400	200
5	400	100

8. A company is considering the projects given in Table 2.15.

Table 2.15 Cash flow for two competing projects.

	End of year	Project *A*	Project *B*
Investment (\$)	0	210,000	50,000
Net cash inflows (\$)	1	70,000	20,000
	2	70,000	20,000
	3	70,000	20,000
	4	70,000	20,000
	5	70,000	20,000

   For both projects, calculate the following.
   a. The payback time for each project in terms of the average annual cash flow
   b. The net present value at the current lending interest rate of 10%
   c. The discounted cash flow rate of return.

   On the basis of a comparison of these three measures, which project would you prefer? Explain your decision.

9. A process has been developed for a new product for which the market is uncertain. A plant to produce 50,000 $t \cdot y^{-1}$ requires an investment of \$10,000,000, and the expected project life is five years. Fixed operating costs are expected to be \$750,000 y^{-1}, and variable operating costs (excluding raw materials) expected to be \$40 t^{-1} product. The stoichiometric raw material costs are \$80 t^{-1} product. The yield of product per ton of raw material is 80%. Tax is paid in the same year as the relevant profit is made at a rate of 35%. Calculate the selling price of the product to give a minimum acceptable discounted cash flowrate of return of 15% year.
10. How can the concept of simple payback be improved to give a more meaningful measure of project profitability?
11. It is proposed to build a plant to produce 170,000 $t \cdot y^{-1}$ of a commodity chemical. A study of the supply and demand projections for the product indicates that current installed capacity in the industry is 6.8×10^6 $t \cdot y^{-1}$, whereas total production is running at 5.0×10^6 $t \cdot y^{-1}$. Maximum plant utilization is thought to be around 90%. If the demand for the product is expected to grow at 8% per year, and it will take 3 years to commission a new plant from the start of a project, what do you conclude about the prospect for the proposed project?

REFERENCES

1. Guthrie KM (1969) Data and Techniques for Preliminary Capital Cost Estimating, *Chem Eng*, **76**: 114.
2. Anson HA (1977) *A New Guide to Capital Cost Estimating*, IChemE, UK.
3. Hall RS, Matley J and McNaughton KJ (1982) Current Costs of Process Equipment, *Chem Eng*, **89**: 80.
4. Ulrich GD (1984) *A Guide to Chemical Engineering Process Design and Economics*, John Wiley, New York.
5. Hall RS, Vatavuk WM and Matley J (1988) Estimating Process Equipment Costs, *Chem Eng*, **95**: 66.
6. Remer DS and Chai LH (1990) Design Cost Factors for Scaling-up Engineering Equipment, *Chem Eng Prog*, **86**: 77.
7. Gerrard AM (2000) *Guide to Capital Cost Estimating*, 4th Edition, IChemE, UK.
8. Peters MS, Timmerhaus KD and West RE (2003) *Plant Design and Economics for Chemical Engineers*, 5th Edition, McGraw-Hill, New York.
9. Mulet A, Corripio AB and Evans LB (1981) Estimate Costs of Pressure Vessels Via Correlations, *Chem Eng*, **Oct**: 145.
10. Mulet A, Corripio AB and Evans LB (1981) Estimate Costs of Distillation and Absorption Towers Via Correlations, *Chem Eng*, **Dec**: 77.
11. Lang HJ (1947) Cost Relationships in Preliminary Cost Estimation, *Chem Eng*, **54**: 117.
12. Hand WE (1958) From Flowsheet to Cost Estimate, *Petrol Refiner*, **37**: 331.
13. Bauman HC (1955) Estimating Costs of Process Auxiliaries, *Chem Eng Prog*, **51**: 45.
14. Holland FA, Watson FA and Wilkinson JK (1983) *Introduction to Process Economics*, 2nd Edition, John Wiley, New York.
15. Brennan D (1998) *Process Industry Economics*, IChemE, UK.
16. Gary JH and Handwerk GE (2001) *Petroleum Refining Technology and Economics*, 4th Edition, Marcel Dekker.
17. Bravo JL (1997) Select Structured Packings or Trays? *Chem Eng Prog*, **July**: 36.
18. Allen DH, (1980) *A Guide to the Economic Evaluation of Projects*, IChemE, Rugby, UK.

Appendix A Annualization of Capital Cost

Derivation of Equation 2.7 is as follows[1]. Let

P = present worth of estimated capital cost

F = future worth of estimated capital cost

i = fractional interest rate per year

n = number of years

After the first year, the future worth F of the capital cost present value P is given by:

$$F(1) = P + Pi = P(1+i) \tag{A.1}$$

After the second year, the worth is:

$$\begin{aligned} F(2) &= P(1+i) + P(1+i)i \\ &= P(1+i)^2 \end{aligned} \tag{A.2}$$

After the third year, the worth is:

$$\begin{aligned} F(3) &= P(1+i)^2 + P(1+i)^2 i \\ &= P(1+i)^3 \end{aligned} \tag{A.3}$$

After year n, the worth is:

$$F(n) = P(1+i)^n \tag{A.4}$$

Equation A.4 is normally written as:

$$F = P(1+i)^n \tag{A.5}$$

Take the capital cost and spread it as a series of equal annual payments A made at the end of each year, over n years. The first payment gains interest over $(n-1)$ years, and its future value after $(n-1)$ years is:

$$F = A(1+i)^{n-1} \tag{A.6}$$

The future worth of the second annual payment after $(n-2)$ years is:

$$F = A(1+i)^{n-2} \tag{A.7}$$

The combined worth of all the annual payments is:

$$\begin{aligned} F = A[&(1+i)^{n-1} + (1+i)^{n-2} + (1+i)^{n-3} \\ &+ \cdots + (1+i)^{n-n}] \end{aligned} \tag{A.8}$$

Multiplying both sides of this equation by $(1+i)$ gives:

$$\begin{aligned} F(1+i) = A[&(1+i)^n + (1+i)^{n-1} + (1+i)^{n-2} \\ &+ \cdots + (1+i)] \end{aligned} \tag{A.9}$$

Subtracting the Equations A.8 and A.9 gives:

$$F(1+i) - F = A[(1+i)^n - 1] \tag{A.10}$$

which on rearranging gives:

$$F = \frac{A[(1+i)^n - 1]}{i} \tag{A.11}$$

Combining Equation A.11 with Equation A.5 gives:

$$A = \frac{P[i(1+i)^n]}{(1+i)^n - 1} \tag{A.12}$$

Thus, Equation 2.7 is obtained.

REFERENCES

1. Holland FA, Watson FA and Wilkinson, JK (1983) *Introduction to Process Economics*, 2nd Edition, Wiley, New York.

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