Chapter 1
Design of Food Processes and Food Processing Plants

1.1 Introduction

Process design refers to the design of food processes and manufacturing methods, including process flow sheets, design of processing and control equipment, and economic evaluation of the process. *Plant design* refers to the design of the whole processing plant, including the processing/control equipment, the utilities, the plant buildings, and the waste treatment units. The two terms are used interchangeably in the technical literature. Both process and plant design are basic parts of feasibility and implementation studies of an industrial project, such as a food processing plant.

The necessary phases for realizing an industrial project include the preliminary study, the feasibility study, and the implementation of the project. The feasibility study includes most of the technical and economic information obtained in process and plant design. The implementation phase involves detailed engineering, construction, supply of equipment, and plant erection and start-up.

The development of food process/plant design is based on the principles of food science and technology, chemical engineering, and on the practical experience of food engineers, chemical engineers, and food technologists. In plant design, the experience and developments in other technical fields, such as materials science, mechanical engineering, and management, should also be considered.

Since the literature on research and development and applications of food process/plant design is limited, it is necessary to review the basics of chemical process/plant design, which will be applied critically in the various chapters of this book.

The unique requirements of design of food processes, food plants, and food processing equipment are considered in more detail in this chapter. The numerous food processing operations are classified in an analogous manner with the established unit operations of chemical engineering. Food processes are represented by the familiar process block diagrams (PBDs) and the process flow diagrams

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(PFDs), which are indispensable for material and energy balances, and preliminary sizing of process equipment.

Some important aspects of food plant design are discussed in the last part of this chapter, emphasizing the need for an integrated approach of hygienic design, food product quality and safety, and cost-effectiveness.

The general aspects of design and selection of food processing equipment are discussed in Chap. 2. Since the final goal of any food plant design is the satisfaction of the consumers, a few elements have been added to this chapter and Chap. 2, concerning the effectiveness of plant design toward this goal.

1.2 Overview of Chemical Process and Plant Design

Chemical process and plant design have been developed mainly in the chemical, petrochemical, and petroleum industries, where very large amounts of materials, usually gases and liquids, are processed continuously into a rather small number of products. The design, operation, and control of these large plants have been advanced in recent years by the use of computers and the availability of data banks of the physical properties of gases and liquids.

Modern process and plant design must reduce raw material costs, capital investment, plant energy consumption, inventory in the plant, and the amount of pollutants generated. The new plants need improved process flexibility, safety, and control technology. Process design should be based more on computer modeling, fundamental principles, and molecular simulations than on today's semiempirical approaches (Edgar 2000).

Process design includes the synthesis, analysis, evaluation, and optimization of process alternatives. Chemical process design is essential in the design of new plants, in the modification or expansion of an existing plant, in the production of a new product, and in the simulation and control of an operating plant. The importance of design is demonstrated by the fact that during the process design (about 2 % of the total project cost), decisions are made that will fix the major portion of the capital and operating expenses of the final plant (Biegler et al. 1997). Economics plays a very important role in any design of chemical processes and chemical plants.

The engineering part of a design project involves basically the development of the process flow sheet, the material and energy balances, and the sizing of the process equipment. In addition, the following essential components of the process plant should be considered: plant location, utilities, plant layout, buildings (architectural and civil engineering), plant operation and control, health and safety, waste disposal, personnel, and legal requirements (restrictions).

Continuous processes are generally preferred over batch processes in the large chemical, petrochemical, and petroleum industries, because they are less expensive in both equipment and operating costs. Batch processes may prove more economical for smaller plants and for food, pharmaceutical, and specialty products. Batch processes are also preferred when little information is available, when process/products have relatively short life cycles, or when a variety of products are produced in small quantities.

Although considerable progress has been made on the application of modeling and computers to the design of chemical processes and plants, design continues to rely largely on the practical experience and the "art" of design engineers. In the design process, a balance of many technical, operational, and economic factors must be considered (Sandler and Luckiewicz 1987; Liu et al. 1988; Wells and Rose 1986).

1.2.1 Process Flow Sheets

Process flow sheets represent graphically the required process equipment and the flow of materials and utilities in an industrial plant. The simplest diagram of a process is the *process block diagram* (PBD), which is used mainly for material and energy balances. The most important representation is the *process flow sheet diagram* (PFD), which is used in the preliminary design of process equipment and processing plants. The *process control diagram* (PCD) shows the automatic control of the processing plant, and the *piping and instrumentation diagram* (PID) indicates the details of piping and process instrumentation of the plant. The PFD, PID, and PCD are used in the detailed process/plant design.

The analysis, selection, and optimization of the process flow sheets (PFDs) are essential in large-scale processing plants, where process economics is very important. Combinations of PFD and analytical tables of materials, energy, and labor requirements in each stage are useful, especially when performing an economic analysis of the process. Systematic synthesis models (Biegler et al. 1997) have recently replaced the intuitive flow sheet development. Numerical solutions and computer techniques are used to solve complex flow sheet problems.

In more complex plant designs, techniques of operations research are used. The Gantt and the PERT diagrams enable the time scheduling and realization of a process and indicate the task priorities in achieving a goal (Hausmann 1987; Lokyer et al. 1989).

1.2.2 Types of Process Designs

There are several types of process and plant design, ranging from simple estimations of low-accuracy to high-accuracy detailed designs. Simple and preliminary estimates are employed to obtain an approximate idea of the required equipment and investment, while a detailed design with drawings and specifications is used for the construction, operation, and control of the processing plant.

Table 1.1 Types of chemical process design

Design/estimate	Accuracy, %	Design cost, % of investment
Ratio estimate	40	0.1
Factored estimate	25	0.2
Preliminary estimate	15	1.0
Definitive estimate	10	1.5
Detailed design	5	2.5

Data from Peters and Timmerhaus (1990)

Table 1.1 shows five types of process estimates and designs of increasing accuracy and design cost (Peters and Timmerhaus 1990; Sinnott 1996). The *ratio* or *order of magnitude estimate* is based on data from a similar previous process/plant. The *factored* or *study estimate* is based on known data of major equipment. The *preliminary* or *budget authorization estimate* is based on sufficient data to proceed with the design project. The *definitive* or *project control estimate* is based on almost complete data before preparing the drawings and specifications. The *detailed design* or *the contractor's estimate* is based on complete data, engineering drawings, and specifications for equipment and plant site. The accuracy of the estimation varies from 40 % (ratio method) to 5 % (detailed design).

The first three estimation methods of Table 1.1 are also known as *predesign estimates*. The most common cost estimates are the preliminary and detailed designs with accuracies of 15 and 5 %, respectively. The cost of preparing the process design as a percentage of the total investment, shown in Table 1.1, is indicative and it depends on the investment, being substantially lower for large projects (Perry and Green 1984; Peters and Timmerhaus 1990). The time required for preparing the preliminary and detailed process designs varies with the complexity and size of the project, being typically about 8 and 12 months, respectively.

1.2.3 *Material and Energy Balances*

The design of process equipment and plant utilities is based primarily on material and energy (heat) balances, which are usually calculated on the PBD. Some approximations are necessary to reduce and simplify the time-consuming calculations, especially for large, complex processing plants, e.g., feed enters the various units at saturation temperature.

Two general methods of calculations are usually applied: the modular and the equation-oriented approach (Biegler et al. 1997). In the modular approach, three types of equations are solved separately: (1) the connectivity equations of the units of the flow sheet, (2) the transport rate and equilibrium equations for each unit, and (3) the equations for the physical, thermodynamic, equilibrium, and transport properties. In the equation-oriented mode, all of the process equations are combined (material/energy balances, thermodynamic and transport, equipment performance, kinetics, and physical property) into a large, sparse equation set, which is solved simultaneously, usually applying a Newton-type equation solver.

The models for material/energy balances are simplified into linear equations by assuming ideal solutions and saturated liquid or vapor streams. The calculations of material and energy balances are usually made by hand or by PC computers, using simple Excel spreadsheets or data tables. For complex, nonideal processes, rigorous methods are employed, requiring special computer algorithms. The physical and transport properties of the materials are obtained from standard books or databases.

1.2.4 Design of Equipment

In preliminary estimations, the approximate size of the process equipment is needed for economic evaluation and subsequent detailed calculations for the processing plant. Material and energy balances, based on the process flow sheet, are used as a basis for the estimation of the various units. A fixed feed rate is assumed (kg/h or tons/h) and all of the materials and heat flows in each unit are calculated.

Transport rate equations and equilibrium relationships are used, including mechanical transfer (pumping), heat transfer, mass transfer, reaction rate, and phase equilibria (vapor/liquid, liquid/liquid, and fluid/solid).

The physical and engineering properties of the materials being processed are needed under the actual conditions of concentration, temperature, and pressure. Data of physical and transport properties are obtained from standard literature texts (Perry and Green 1984, 1997; Reid et al. 1987) or databases (DIPMIX 1997).

Transport properties and heat and mass transfer coefficients are difficult to predict theoretically, and experimental or empirical values, appropriate for the specific equipment and process conditions, are normally used. Computer programs are used in calculations of the various unit operations of the process plant. Such programs are part of the large computer packages used in process simulations, but simpler software for personal computers is available (CEP 2000).

In several cases, such as in handling of equipment or in relation among workers/operators/manufactured product and equipment involved, the factor “human being” has also to be considered. Here, knowledge of work study can be very helpful.

Empirical data and “rules of thumb” are used to facilitate the various design calculations, such as the design velocities (u) in process pipes, e.g., u (liquid) = 1.5 m/s and u (gas/vapor) = 30 m/s, water pressure in pipes (4–6 bars), and overall heat transfer coefficients (natural convection of air near walls, 10 W/m^2 K, and forced circulation of thin liquids in pipes, 2000 W/m^2 K).

The design of chemical process equipment is based on the principles of unit operations and process engineering. In analyzing the various industrial processes, simplified equations and shortcut methods are often used (Bhatia 1979–1983; Sandler and Luckiewicz 1987; Walas 1988).

Equipment design yields quantitative data on required equipment, such as dimensions of pipes, power of pumps, surface area of heat exchangers, surface area of evaporator heaters, dimensions of distillation or extraction columns, and dimensions of dryers. In addition, the approximate quantities of the required plant utilities are calculated. In equipment sizing, a safety or overdesign factor of 15–20 % is normally used.

After the preliminary sizing of the process equipment, detailed specifications are set, which are necessary for purchasing the equipment from the suppliers. At this stage, a preliminary cost estimate of the equipment is made, using cost indices and other methods, outlined in Sect. 1.2.6 on economic analysis. Whenever possible, standard or "off-the-shelf" equipment should be used, which is generally less expensive and more reliable than nonstandard equipment. Standard equipment includes pumps, heat exchangers, valves, standard evaporators, distillation columns, and centrifuges.

When specialized or nonconventional equipment is needed, detailed specifications are required which will help the fabricator to construct the appropriate unit (e.g., filters, chemical reactors, special dryers, and distillation columns). Sometimes, special equipment is needed for a new process, for which there is no industrial experience. In such cases, a pilot plant installation may be required, which will supply the specifications for the desired industrial equipment. The scale-up ratio of capacities (industrial/pilot plant) is usually higher than 100:1.

The utilities or auxiliary facilities, which are necessary for the operation of the processing plants, include energy, water, steam, electricity, compressed air, refrigeration, and waste disposal. Energy in the form of heat or electricity is needed for the operation of the plant. Heat is produced primarily by combustion of fuels (oil, gas, and coal). Water is supplied from the municipality or from the surrounding plant area (drilled wells, rivers, or lakes) and is required for process, sanitary, and safety uses. High-pressure steam may be used for power generation, and the exhaust steam is utilized for process heating. Waste disposal involves the treatment of liquid, gas/vapor, and solid wastes (see Appendix D).

The selection of the materials of construction of process equipment is very important from the economic, operational, and maintenance points of view. Corrosion-resistant materials such as stainless steels may be required in handling and processing corrosive fluids. National and international construction codes are necessary for plant and worker protection and for standardization of the process equipment (see Chap. 2). Some of the codes related to chemical process equipment are ASME (pressure vessels), TEMA (heat exchangers), ANSI (piping and instrumentation), and DIN (materials and construction).

1.2.5 Plant Layout and Buildings

The layout of process and utility equipment is essential to ensure the safety, operability, and economic viability of any process plant and for planning future extensions. A balance of many technical, operational, and economic factors must be achieved. Plant layout follows the development of the PFD and the preliminary sizing of the process equipment and is necessary before piping, structural, and electrical design. The layout of equipment should allow for a safe distance between the units, facilitating the operation, servicing, and cleaning of each unit.

Plant layout is shown in engineering drawings or, if plants are more complex, in 3D models, which are useful for construction engineers and for instruction of plant operators.

Plant buildings are needed mainly to house the process and utility equipment, the storage areas, the plant offices and labs, and the personnel common rooms (cafeterias, washrooms). In choosing the plant location, several factors should be considered, including raw materials, markets for the products, energy and water supplies, waste disposal, labor supply, legal restrictions, and living conditions. In some large petroleum and petrochemical plants, several large units and the required piping are installed outside the buildings (e.g., distillation columns, storage tanks).

In the installation of plant equipment, special attention should be paid to the foundations of the heavy units, considering also any vibrations of rotating/reciprocating equipment. In the construction of industrial buildings, the local and federal (national) regulations and codes should be followed, particularly those that are related to the health and safety of the workers and the consumers and the protection of the natural environment.

1.2.6 Economic Analysis in Process/Plant Design

1.2.6.1 Fixed Capital Investment

Cost analysis is an important part of process and plant design. Fixed capital investment in process equipment, manufacturing costs, and general expenses should be considered in the early stages of design.

The fixed capital investment in process plants consists of a number of items, which depend on the type of plant and the manufactured products. Table 1.2 shows the important cost items and their percentages of the fixed capital investment for a typical chemical plant (Peters and Timmerhaus 1990). It should be noted that the cost of piping in chemical, petrochemical, and petroleum plants (mostly gas/liquid processing) is relatively high, compared to other processing industries, such as pharmaceuticals and foods (mostly solids processing).

The contingency item refers to unexpected approximate costs of the project. In addition, a working capital of about 20 % of the fixed capital may be needed for the initial operation of the plant.

The installed utilities, representing about 15 % of the fixed capital, include auxiliary buildings (5 %), steam (4 %), water supply (3 %), waste treatment (1 %), electrical (1 %), and compressed air (1 %) (Perry and Green 1984).

The fixed capital investment for a chemical plant can also be estimated by empirical rules or approximations, which yield results similar to those of Table 1.2. Thus, the fixed capital (FC) can be broken down into four basic components, related

Table 1.2 Fixed capital investment for typical chemical plant

Item of fixed capital	% of fixed capital cost
Purchased equipment	23.0
Equipment installation	12.0
Piping, installed	14.0
Instrumentation and control	5.0
Electrical	3.0
Utilities, installed	15.0
Buildings and construction	12.0
Engineering	8.0
Contingency	8.0

Data from Peters and Timmerhaus (1990)

to the mechanical equipment (ME), electrical equipment (EE), plant buildings and site or civil engineering works (CE), and overhead (OV), according to the following fractional proportions (Sinnott 1996):

$$1.00\,\mathrm{FC} = 0.37\,\mathrm{ME} + 0.08\,\mathrm{EE} + 0.29\,\mathrm{CE} + 0.26\,\mathrm{OV} \tag{1.1}$$

The fixed capital can also be estimated from the process equipment cost (EC) by the factorial method:

$$\mathrm{FC} = f_{\mathrm{L}}\,\mathrm{EC} \tag{1.2}$$

where the factor f_{L}, or the Lang factor, is equal to 3.1 for solids processing, 4.7 for fluids processing, and 3.6 for mixed fluids/solids processing.

In food processing, the installation, piping, and instrumentation and control costs are smaller than in chemical processing. The base equipment is more expensive (stainless steel, hygienic requirements) than the chemical equipment. As a result, the empirical Lang factor (f_{L}) in food processing plants varies in the range of 1.5–2.5 (Bartholomai 1987; Clark 1997b).

The fixed capital investment can be considered as consisting of two parts, the fixed manufacturing component (FM), which includes the cost of equipment and 25 % contingency, and the fixed nonmanufacturing component (FN). Typically, FN = 0.4 FM.

The working capital for a processing plant can be taken approximately as 20 % of the fixed capital.

1.2.6.2 Cost of Equipment

The most accurate cost estimation for process equipment is to obtain a price quotation from a reliable vendor (supplier of equipment). Specification sheets for each process unit should be prepared for the equipment supplier. The specifications should contain basic design data, materials of construction, and special information that will help the supplier to provide the appropriate equipment. Standardized equipment should be preferred because of lower cost and faster delivery.

When approximate cost data are required for preliminary design, empirical methods and rules are used, which will yield fast results within the accepted accuracy (Chilton 1960). A popular method is to use the Guthrie charts of equipment cost versus capacity (Guthrie 1969; Peters and Timmerhaus 1990; Perry and Green 1984; Douglas 1988). Plotted on log–log scales, the Guthrie charts show straight lines. These charts are represented by the generalized cost–capacity equation:

$$C = C_o(Q/Q_o)^n \tag{1.3}$$

where C and C_o are the equipment costs (e.g., USD) at plant capacities Q and Q_o (e.g., kg/h), respectively.

The capacity factor (n) varies with the type of equipment over the range 0.5–1.0 and is taken approximately as $n = 2/3$. The "2/3" factor has a theoretical basis, since the cost of spherical vessels is given by the relationship $C = k\ V^{2/3}$, where V is the vessel volume and k is a constant (Biegler et al. 1997).

Figure 1.1 shows a log–log plot of the cost of long-tube vertical evaporators, estimated from the data of Peters and Timmerhaus (1990) for stainless steel 304 and converted to year 2000, using the M&S index. The capacity factor in this case is $n = 0.53$.

The plant capacity–cost relationship (Eq. 1.3) is normally applied to equipment and utilities of the main chemical processes. Better cost estimates can be obtained by modifying Eq. (1.3), taking into consideration the cost of all auxiliaries outside the main process, such as environmental installations and materials handling and storage (Haseltine 1986).

1.2.6.3 Engineering Cost Indices

The cost of process equipment and processing plants changes over the years, due to inflation and other economic factors, and there is a constant need for updating the

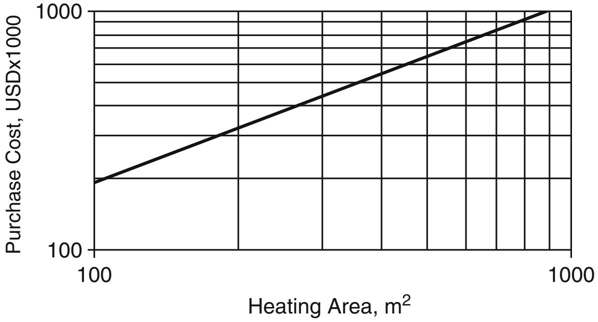


Fig. 1.1 Guthrie chart for long-tube evaporators (stainless steel, 2000 prices). Data from Peters and Timmerhaus (1990)

cost data. For this reason, cost indices or empirical rules are used, like the M&S index (Marshall and Swift, formerly Marshall and Stevens), published periodically in the journal *Chemical Engineering*.

The M&S equipment index is the weighted average of the cost of equipment for eight chemical process industries, including chemicals, petroleum, and paper. It takes into consideration the cost of machinery and major equipment, plus costs of installation, fixtures, tools, office furniture, and other minor equipment. The basis of the M&S index = 100 is the year 1926.

The CE (chemical engineering) plant cost index, also published in the journal *Chemical Engineering*, is the weighted average of chemical plant costs (66 items, including equipment, buildings, and engineering).

Figure 1.2 shows the continued increase of both indices during the last 35 years, with a sharp rise during the decade 1970–1980, due to rising energy costs, and a leveling off after 1990. Cost indices are approximate mean values with variations up to 10 % and recent annual inflation of about 4.5 %.

Although most of the engineering indices refer to the US industry, they are applied to chemical industries in other parts of the world, with little correction (Perry and Green 1984). Country-specific plant construction indices, based on the CE index, can be developed, using approximate models, the constants of which can be determined by fitting local cost data (CE 1997). These models take into account the following main items: local steel price, labor cost, inflation index, and crude oil index. In case of limited operation of equipment due to early replacement, their effective retail value should be also considered (see also p. 38).

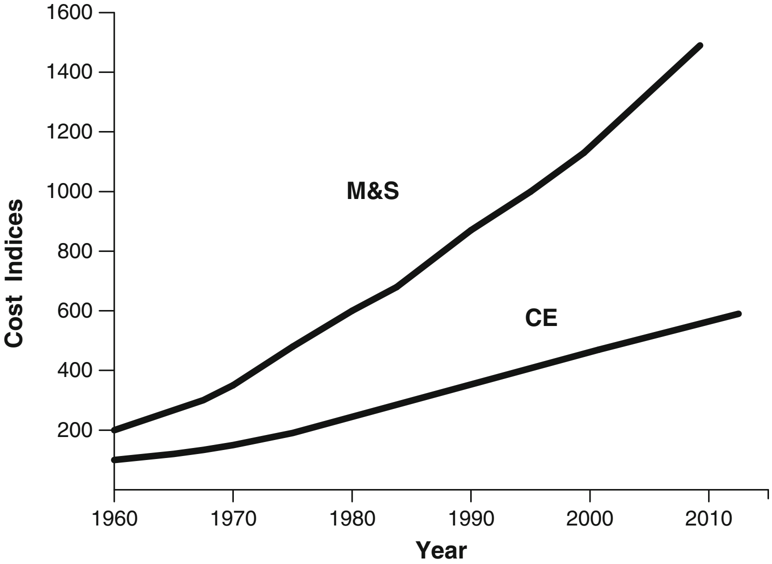


Fig. 1.2 Marshall and Swift (M&S) and chemical engineering (CE) cost indices. Data from the *Journal of Chemical Engineering*

1.2.7 Manufacturing Cost and Profitability

1.2.7.1 Manufacturing Cost

Although the main objective of process economics is the profit on the invested capital, some other criteria should also be considered in designing and building a chemical process plant. The plant should be operated and controlled safely for the workers, the products should be safe and without adverse health effects to the consumers, and the environment should not be damaged by plant wastes.

The economic analysis of chemical processes and chemical plants is covered in Perry and Green (1984), Douglas (1988), Peters and Timmerhaus (1990), and in specialized economics books. The elements of process economics, needed for preliminary design, are summarized here.

The manufacturing cost, usually calculated in USD/year, consists of two basic parts: (1) the direct or variable operating cost, which includes the cost of raw materials, labor, utilities, and overhead and the administrative costs, and (2) the indirect or fixed charges (USD/year), consisting of the depreciation of the fixed investment and the taxes/insurance. Depreciation is usually taken as 8 % of the fixed investment, i.e., the fixed capital will be recovered in 12 years. The product cost (USD/kg) is calculated by dividing the manufacturing cost by the annual production rate (kg/year) (Table 1.3).

1.2.7.2 Profitability

Process profitability can be estimated by the following simple economic calculations (Biegler et al. 1997):

Table 1.3 Approximate cost indices for process equipment (M&S) and plants (CE)

Year	M&S index	CE index
1960	230	100
1965	240	105
1970	300	120
1975	440	180
1980	610	240
1985	800	305
1990	915	360
1995	1030	380
2000	1100	385
2005	1300	500
2010	1510	550
2012	–	600

Data from the *Journal of Chemical Engineering*

$$\text{gross profit} = \text{gross sales} - \text{manufacturing cost} \tag{1.4}$$

$$\text{gross profit before taxes} = \text{gross profit} - \text{sales etc. expenses} \tag{1.5}$$

$$\text{net annual cash flow} = \text{gross profit before taxes} - \text{taxes} \tag{1.6}$$

$$\text{return on investment} = \mathrm{ACF}/\mathrm{FI} \tag{1.7}$$

$$\text{payback time} = \mathrm{FI}/(\mathrm{ACF} + \mathrm{AD}) \tag{1.8}$$

where FI is the fixed investment, ACF is the net annual cash flow, and AD is the annual depreciation.

The payback time (Eq. 1.8) is the time of plant operation, usually in years, at which the cumulative cash flow becomes equal to zero. In the first years of operation, the ACF is negative, due to the high operating cost, but it turns into a positive net cash flow, after the payback time. An alternative method of estimating the payback time is

$$_{1}\Sigma^{n}\mathrm{ACF}_{n} = 0 \tag{1.9}$$

The previous simplified economic analysis can be used in preliminary design and approximate cost estimations. However, it does not consider the "value of money," i.e., the interest that could be earned from the fixed invested capital. In detailed design and in actual economic evaluations, the prevailing interest rate is taken into account in the form of "discounted" cash flows (Perry and Green 1984).

The annual discounted cash flow (ADCF) is related to the ACF:

$$\mathrm{ADCF} = f_{\mathrm{d}}\mathrm{ACF} \tag{1.10}$$

where $f_{\mathrm{d}} = 1/(1 + i)^{n}$ is the discounted factor, i is the fractional interest rate (yearly basis), and n is the number of years.

The cumulative (sum) of the ADCF after n years is defined as the net present value (NPV) and is calculated from the following summation:

$$\mathrm{NPV} {=}_{1}\Sigma^{n}\mathrm{ADCF}_{n}/(1 + i)^{n} \tag{1.11}$$

The discounted cash flow rate of return (DCFRR) or return on investment (ROI) is the fractional interest rate (i) for which NTV becomes equal to zero, after a chosen number of years (n), and it is calculated as follows, using a graphical or a trial-and-error iteration technique:

$$_{1}\Sigma^{n}\mathrm{ADCF}_{n}/(1 + i)^{n} = 0 \tag{1.12}$$

The DCFRR is also known as the profitability index, initial rate of return (IRR), or investor's rate of return.

In economic planning, the cost of replacement of major process equipment, after a number of years, should be considered. This is accomplished by reserving the replacement cost (RC) of the equipment, which is converted to the capitalized cost (CC), using the prevailing annual interest rate (i), according to the following equation (Clark 1997b):

$$\mathrm{CC} = \mathrm{RC}(1+i)^n/[(1+i)^n - 1] \tag{1.13}$$

The capitalized cost, estimated from Eq. (1.13), assumes that the equipment has no salvage value after n years of operation.

1.2.7.3 Breakeven Point

The processing plant should be operated so that the total income is higher than the total product (operating) cost and a reasonable profit is realized. At low rates of production, the total income is lower than the total product cost, because the fixed costs (e.g., depreciation, maintenance) remain constant and a financial loss is obtained. The rate of production above which the operation is profitable is called the "breakeven point," as shown in Fig. 1.3.

In some processing systems, like the one shown in Fig. 1.3, there is an optimum operating rate of production (point M), where the net profit is maximized (Peters and Timmerhaus 1990). In the generalized diagram of Fig. 1.3, the "breakeven" point is at a production capacity of about 50 % of the maximum plant capacity, and the optimum operation is at about 80 % of maximum capacity. For a combination of reasons, the optimum operating capacity may not be the maximum production capacity.

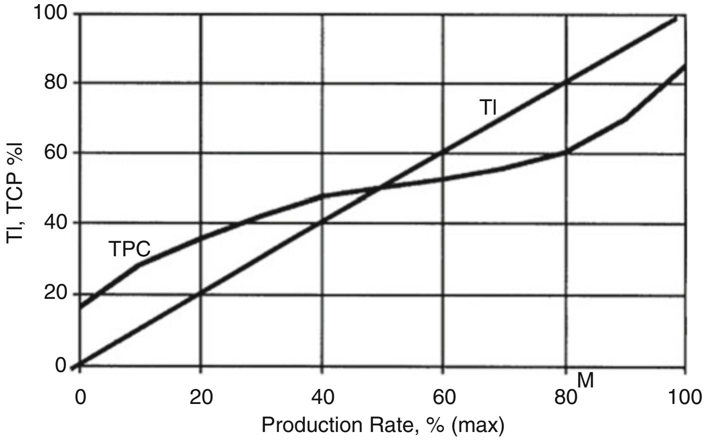


Fig. 1.3 Production rate-related "breakeven diagram of a processing plant. *TI* total income, *TPC* total product cost, *M* maximum profit

1.2.8 Computer-Aided Process/Plant Design

Although the design of chemical processes and chemical plants has been based until recently on practical experience and empirical rules, there has been a lot of activity on the applications of computer-aided techniques in this important area of chemical engineering. Computer-aided process engineering (CAPE) has been the favorite subject of university and industrial research and development projects, directed primarily to large-scale chemical and petrochemical processes, both in the USA and in other parts of the world. Process design, which is the major component of CAPE, is a major subject of the annual European Symposium on Computer-Aided Process Engineering (ESCAPE), the proceedings of which are published in the journal *Computers and Chemical Engineering*.

Most of the progress in CAPE has been in the modeling, simulation, and optimization of chemical processes, with emphasis on flow sheet development, separation processes, and energy utilization. The processing of gases and liquids has received particular attention, due largely to the availability of reliable prediction methods and databanks of the physical, thermodynamic, and transport properties of the materials being processed. Limited attention has been given to the processing of solids and semisolids, due to difficulties in modeling and to insufficient data on engineering properties.

In preliminary calculations for process design, general-purpose software is used, such as the Excel spreadsheets (Maroulis and Saravacos 2003). For process simulation, large systems, like ASPEN PLUS (Aspen Technology Inc.), (Aspen 2001), HYSIM/HYSYS (Hyprotech Ltd.), and PRO II (Simulation Sciences), are used (Sinnott 1996). The international CAPE system, developed by a consortium of universities and industries, can be applied to various process industries.

Several computer programs have been adapted for use in PCs, utilizing simplified software (e.g., Microsoft Windows). A list of such programs, convenient for preliminary design and costing of chemical process equipment and plants, is published annually in the CEP Software Directory (CEP 2000).

The computer-aided design (CAD) programs usually consist of an executive system; packages of physical, thermodynamic, and transport properties; and collections of design subroutines for various process units (Douglas 1988). CAD software is available for preparing process flow sheets, piping and instrumentation diagrams, and engineering drawings of chemical equipment and chemical plants. Two-dimensional (2D) drawings are normally used, but in special cases, three-dimensional (3D) drawings offer a better visualization of t instrumentation diahe process or the whole plant (CE 1999).

1.3 Design of Food Processes

The identification of food engineering and its objectives within food science is described by Kostaropoulos (2012). Systematic process design is gradually adopted in the design of food processes, replacing the empirical approaches of the past. In addition to the principles and techniques of chemical process design, the design of food processes must be based on the principles and technology of food science and engineering.

Successful and efficient manufacturing technologies, developed in other industries, can be adapted, modified, and implemented in the food industry. Food quality and food safety must receive special consideration, while applying the engineering principles and techniques.

Food processing involves several physical unit operations and microbiological, biochemical, and chemical processes, which aim at preservation and improvement of food quality or conversion to safe and nutritional food products in large, economic scale. Food preservation and conversion technology has advanced considerably in recent years (Fellows 1990; Heldman and Hartel 1997).

Food engineering has evolved into an interdisciplinary area of applied science and engineering, based primarily on chemical engineering and food science. The traditional unit operations of chemical engineering have been adapted to food processing, taking into consideration the complexity of food materials and their sensitivity to processing conditions (Leniger and Beverloo 1975; Loncin and Merson 1979; Heldman and Lund 1992; Valentas et al. 1997).

The physical operations of food processing can be analyzed by applying the established concepts of unit operations and transport phenomena of chemical engineering (Gekas 1992; Fryer et al. 1997). In addition to the traditional engineering considerations of process cost, energy optimization, and process control, demands on food quality and safety should be satisfied. In this respect, application of the principles and advances of food science is essential.

The trend for improved product quality in all industries (product engineering) should be taken into consideration in all stages of process design. In the food industry, advances in the developing field of food materials science should be considered, with respect to the effect of food handling, processing, and storage on the structure and quality of food products (Aguilera 2000).

Process control and automation, adapted from other industries, must take into consideration the requirements of accurate control of safe thermal processing, time–temperature effects on product quality, and desired micro- and macrostructure of food products.

In the food industry, the trend for improved products (product engineering) should be taken into consideration in all stages of process design (Aguilera 2000). This involves all aspects, starting with the processing of “raw materials” or with the further processing of prefabricated products. Besides food manufacturing, an efficient design should also take into consideration aspects of supply, handling, and storage, and the successive kind of food trade (e.g. import-export, wholesale, cash and carry types of delivery markets and marketing) up to the final consumption of food.

In *manufacturing*, the basic requirements are (1) manufacturing of high-added-value products; (2) constant output of manufactured products, as far as possible; and (3) permanently constant high quality of produced food.

In *trade*, the requirements are (1) constant supply of food to the consumers, (2) constant good quality of the retail products, (3) compliance with the specifications and standards, (4) possibility to extend the shelf life of the products, and (5) facility in handling, including transportation.

In *consumption*, the requirements are (1) increase of assortment of products, (2) satisfaction of an easy-to-use trend, (3) good quality, and (4) reasonable price.

The *quality* requirements are (1) safety of food [e.g., no transfer of infection or contamination], (2) dietary suitability [e.g., adequate nutrition], (3) process suitability [e.g., the right initial raw food material for manufacturing certain foods], and (4) sensory characteristics, such as odor and optical properties, texture, acoustic properties (e.g., crispy products), and taste.

Basic elements for improvement of food quality are marketing and research. Figure 1.4 gives an overview of the improvement tasks of the "cycle": food marketing–food development–food processing–consumption.

The procedure of introducing new products in the market is indicated in Fig. 1.5. It is important to foresee the right time that a product has to be renewed or replaced (e.g., M'_1 for product A and M'_2 for product B). For estimating M'_1 and M'_2, the tangents on the breaking points of the curves are drawn: Total sales of a product as function of time are drawn, and M_1 and M_2 are the points where the verticals from points M'_1 and M'_2 meet the x-axis (time). Furthermore, each new replacement should surpass the already achieved sales of the removed product. The term "new products" does not always refer to essentially new products. As "new" are also characterized products that are based on line extensions or formulations. This includes updating formulations and redesigning packaging (Rudolph 2004).

The introduction of "new" products is essential for the welfare of food factories. However, probably not all products indicated as "new food products" may be really new! There is some disagreement on what a food product may be called "new." Often there is diversification concerning what the industry or the consumers face as new. Often for the industry, the "new" simply reflects only a new appearance such as new packaging or combination of packaging media, "season's adjustments," or extension of already existing products, while the consumers do not agree that new items are not the same as new products.

It is estimated that the number of "new products" of food introduced every year exceeds 8000 (Kontny 1989). As mentioned by Lord (2000), referring to information of the Marketing Intelligence Service Ltd., of about 11,000 new foods introduced in USA in 1996, only 7.2 % featured real innovations. A.C. Nielsen and Litton Matysiak and Wilkes, Inc., reported that only 8.9 % of "new products" in 1995 were actually new. Furthermore, according to a study concerning the 20 most new products introduced by US companies, in which certain restrictions were put

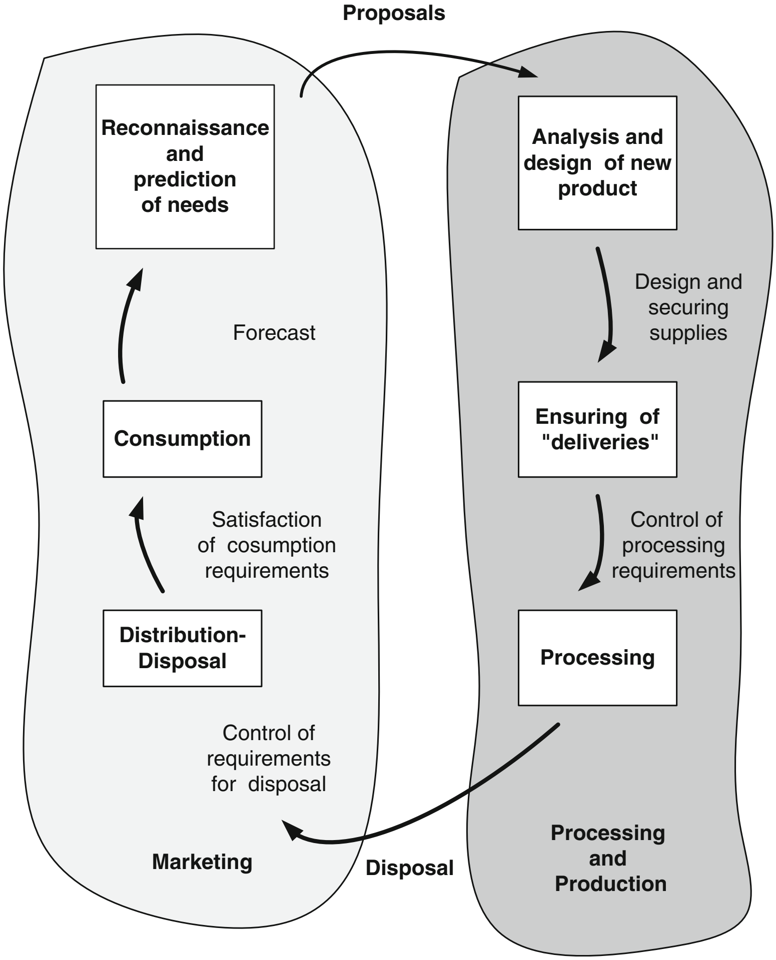


Fig. 1.4 Relation of food processing–marketing

for the use of the term "new," only 9 % of the called "new" products were indeed new (Lord 2000).

A successful investment in research contributes to the long life cycle of a new product in the market. However, only a small number of genuinely new developed products are tested in an actual market, and furthermore, only a smaller part out of them finally survives in the market. Large companies often prefer to cooperate or incorporate the smaller ones when the new invented products promise good market future (see also introduction of Appendix E). However, according to Dornblaser (1997a) cited by Lord (2000), the research profits of larger companies are significant (Fig. 1.6). Successful new products had spent more time on assessment creating clear product definitions (Giese 2003). Often, small companies are more flexible in presenting "new products."

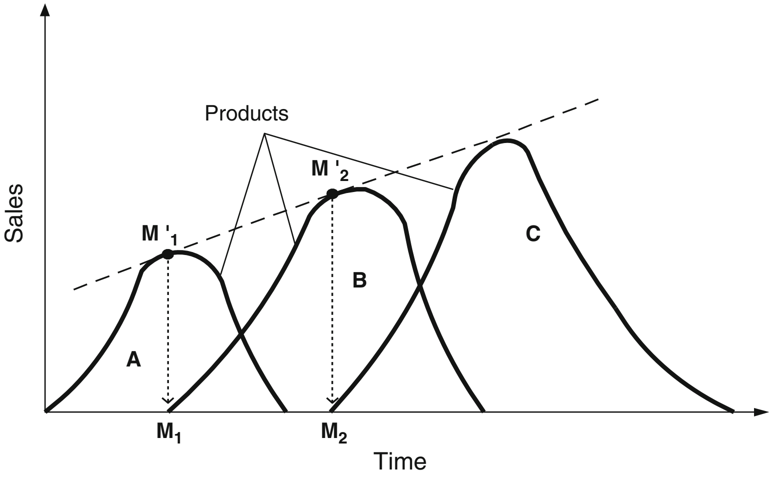


Fig. 1.5 Market replacement of a product

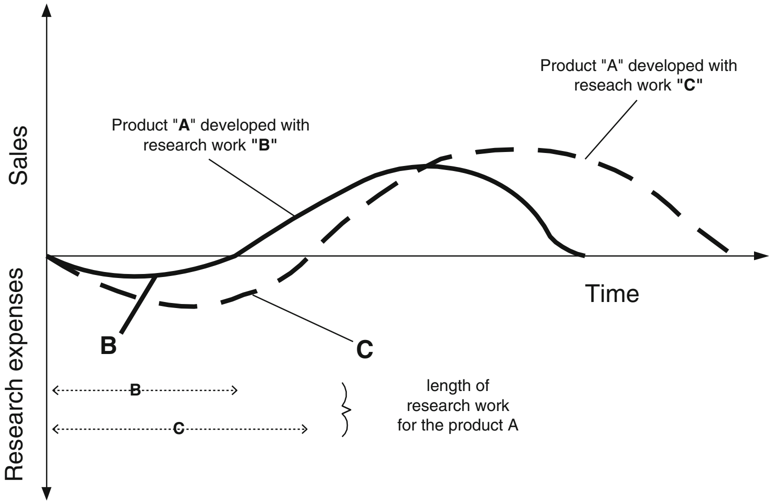


Fig. 1.6 Influence of research on the life cycle of a product

Food plant control should cover the whole spectrum from delivery of raw materials up to consumption. Two main categories of control in food manufacturing may be distinguished: (1) control related to the means of processing/manufacturing and (2) control of products.

1. In processing, control and automation adapted from other industries must take into consideration the requirements of accurate control of safe thermal processing, time–temperature effects on product quality, and the desired

micro- and macrostructure of food products. Control is extended to (a) equipment (condition, maintenance, etc.), (b) operational parameters (conditions of processing), (c) main installations (hydraulic and electric installation, buildings), and (d) auxiliary installations (energy, water supply, wastes, etc.).

2. Product control includes (a) incoming deliveries (raw materials, additives, packaging materials, etc.) and (b) control of products during and after processing (storage, handling, transport, retail). In some cases, it may be extended to controls that are related to environmental factors (quality of water, air, etc.). Main categories of product control are (a) microbiological and biological analyses (decay, infections, etc.), (b) chemical analyses (composition, residual substances, chemical reactions), and (c) technical analyses (packaging material, texture, sensory evaluation, etc.). Details on food quality and safety programs are cited in Sect. 1.4.

1.3.1 Unit Operations in Food Processing

The basic unit operations of chemical engineering, i.e., fluid flow, heat transfer, and mass transfer, have been applied to the food processing industry for many years. The theory on these operations was developed originally for gases and liquids (Newtonian fluids), which constitute the main materials of the chemical industry (Perry and Green 1984). However, food processing (or food manufacturing) deals mostly with non-Newtonian fluids and semisolid and solid food materials, and adaptation or extension of the theory is necessary. Some food processing operations, dealing with such complex materials, are still treated empirically, using rules, practices, and equipment developed through experience (Brennan et al. 1990). A comprehensive review of food process engineering operations is presented by Saravacos and Maroulis (2011).

Due to the diversity of food processes and food products, several specialized unit operations were developed in the food processing industry (Ibarz and Barbosa-Canovas 2002). More than 150 food processing operations were listed by Farkas (1977, 1980). The unit operations were classified into three broad groups, based on the purpose of food processing, i.e., separation (mechanical, physical, thermal, chemical), assembly (mechanical, physicochemical), and preservation (heat, cold, drying, chemical, irradiation). In addition, packaging operations must be considered.

The *separation processes* include mechanical separations (based on size/density and mechanical properties of the materials) and physical separations (based on mass transfer rates of components at interphases). The latter are often listed as mass transfer operations (King 1971). Since most foods are solids or semisolids, several solid/solid separations, developed through experience, are used in food processing operations. Thus, in the processing of fruits and vegetables, the following mechanical operations are applied: abrading, crushing, cutting, dividing, expressing (juice), filtering, finishing, grinding, peeling, pitting, shelling, sieving, sizing, slicing, and stemming.

The *assembly* of food materials is accomplished mostly by mechanical operations. Examples of assembly operations include agglomeration, coating, forming, enrobing, mixing, extrusion, molding, pelleting, stuffing, emulsification, crystallization (from melt), baking, and foaming.

The *preservation operations* of food processing are based on the elimination of the spoilage cause (microbes, enzymes, pests, and chemicals). Preservation operations can be subdivided into three major categories: physical, chemical, and mechanical. The physical operations include heating (frying, boiling, pasteurization, sterilization, blanching, cooking), cooling (chilling, freezing), and drying (dehydration, desiccation, evaporation). Chemical preservation includes permitted chemical substances, such as vinegar and lactic acid. The mechanical operations include cleaning, washing, sorting, and high pressure. However, in some cases of food, mechanical operation is not clear. Extrusion, e.g., is a mechanical as well as thermal (physical) process.

For the purposes of this book, the unit operations of food processing are classified on the basis of the processing equipment, with typical examples shown in Table 1.4. It should be noted that the *unit operations* are defined as physical operations, while the *processes* involve some type of reaction (chemical, biochemical, or microbiological). In this sense, some of the processing operations, listed in Table 1.4, are actually processes, e.g., sterilization (heat transfer and microbiological reaction), blanching (biochemical and physicochemical reactions), and irradiation (energy absorption and microbiological reaction).

Food quality considerations are very important in the selection and operation of processes. Food materials can be considered as either living or nonliving plant (or animal) tissues. In food processing, fresh fruits and vegetables are considered to consist of living tissues. Dried plant foods and animal tissues are generally considered as nonliving tissues. The quality of living tissues is influenced by storage conditions of temperature, relative humidity, and gas atmosphere. In most food processing operations, the food materials consist mostly of nonliving tissues (Farkas 1980).

In fruit and vegetable processing, heat treatment operations, such as blanching, cooking, and sterilization, convert the living into nonliving tissues. Optimization of heat treatment operations is possible, since the rate of destruction of spoilage microorganisms and enzymes is faster than the rate of quality deterioration (undesirable changes in color, flavor, structure, and nutritive value).

A practical description of the unit operations, used in the processing of fruits and vegetables, was presented by Gould (1996). Fruit and vegetable processing is a large industry worldwide, consisting of a large number of small- to medium-sized processing plants and producing several diverse food products. These plants utilize several and often specialized unit operations, since the materials being processed are solids or semisolids, sensitive to mechanical and thermal processing. On the other hand, the dairy, edible oil, milling, and beer industries deal with large amounts of fewer products, utilizing a smaller number of standard unit operations.

Table 1.4 Classification of unit operations of food processing

Group of operations	Typical food processing operations
Mechanical processing (Chaps. 4 and 5)	Peeling, cutting, slicing
	Size reduction
	Sorting, grading
	Mixing, emulsification
Assembly operations (Chap. 4)	Agglomeration
	Extrusion, forming
Mechanical separations (Chap. 5)	Screening
	Cleaning, washing
	Filtration
	Mechanical expression
	Centrifugation
Mechanical transport (Chap. 3)	Pumping of fluids
	Pneumatic conveying
	Hydraulic conveying
	Mechanical conveying
Heat transfer operations (Chaps. 6, 9, and 10)	Heating, blanching
	Cooking, frying
	Pasteurization
	Sterilization
	Evaporation
	Cooling, freezing, thawing
Mass transfer operations (Chaps. 8 and 11)	Drying
	Extraction, distillation
	Absorption, adsorption
	Crystallization from solution
	Ion exchange
Membrane separations (Chap. 12)	Ultrafiltration
	Reverse osmosis
Fermentation	Alcoholic fermentations
	Lactic fermentations
	Dairy fermentations
Nonthermal preservation (Chap. 12)	Irradiation
	High pressure
	Pulsed electric fields
Packaging (Chap. 13)	Filling, closing
	Metallic, plastic packages
	Aseptic packaging
	Modified atmosphere, vacuum

The scale-up methods, used successfully in chemical engineering, are difficult to apply, even to continuous food processing operations, due to the complex physical, chemical, and biological reactions in the food systems. Pilot plant data, under similar processing conditions, are necessary for scale-up to industrial operations of complex food processes, like extrusion cooking of starch-based foods (Valentas et al. 1991) or processing of new foods.

The pilot plant is useful in determining new food processes and in testing new processing equipment under industrial-like operating conditions. It is often used for the production of large samples of new food products, which are needed for storage and marketing tests.

The required unit operations of a food processing plant should be arranged in the proper sequence, i.e., a plant layout should be followed.

A number of empirical specifications and standard practices (good manufacturing practices, GMPs) are necessary for the hygienic and safe operation of food processing equipment and processing plants (Gould 1994; NZIFST 1999). The GMPs are discussed in the Sect. 1.4 and equipment design (Chap. 2).

1.3.2 Food Process Flow Sheets

In food process design, flow sheets similar to those of chemical process design are used, i.e., process block diagrams (PBDs), process flow diagrams (PFDs), process control diagrams (PCDs), and process instrumentation and piping diagrams (PIDs). In addition, Sankey diagrams (Seibel and Spicher 1991) may be used, which present material and energy balances in graphical form. Materials handling diagrams are also useful, since they describe interconnections of processing operations, even if they are located in different buildings or even sites.

The selection of an optimized process flow sheet in the chemical and petrochemical industries requires extensive computer calculations, due to the large number of possible process configurations. However, the realistic process configurations in a given food processing system are limited, because there is usually only one major operation or process in a given flow sheet, which defines more or less the other auxiliary operations.

CAD uses mainly 2D flow sheets for various process, equipment, and plant representations. In special cases, 3D diagrams are useful for a better visualization of complex processing equipment or processing plants (CE 1999), as in grain mills and edible oil processing, where materials transport and piping play a dominant role.

PBDs are normally used for a quick representation of the process and for preliminary calculations of material and energy balances. Each rectangular block represents individual unit operations or group of operations. The PFDs or process flow sheets show more details of the process or plant, using specific symbols for equipment, piping, and utilities. They are simple and any changes may be done easily. Both PBD and PFD flow sheets can show process details, like material flow rates (kg/h), energy flows (kW), temperatures (°C), and pressures (bars). They can be combined with tables of data.

PCD show the position of the control units in the processing lines and their connection to the sensors. PIDs indicate the type and location of instrumentation and the type and connections of pipes. There are no generally accepted standards for process symbols in flow sheets. There are some universally applied symbols for chemical process equipment, listed in the chemical engineering literature, e.g., Walas (1988), Sinnott (1996), and DIN 28004.

In addition to the PBD and PFD, diagrams showing the exact position of the processing equipment in the food plant (ground plans) are also used. Front and side views of the processing line may also be required.

For illustrative purposes, one block diagram and one process flow sheet for the same food processing plant are shown in Figs. 1.7 and 1.8. The plant chosen is a multiproduct facility for orange processing (Nagy et al. 1993; Kimball 1999; Valentas et al. 1991), involving several unit operations and processes and a variety of processing equipment, which will be analyzed in detail in the examples of subsequent chapters of this book.

Figure 1.9 shows a 3D flow sheet for a tomato paste processing plant for better visualization of the plant and equipment. The same tomato paste plant is shown in the form of a process flow sheet (Fig. 1.10) and floor plan or layout of equipment (Fig. 1.11). It should be noted that some of the operations shown in the flow sheets of Figs. 1.7–1.11 might involve more than one piece of equipment. For example, the separation of oil from orange peels may include an oil press, a grinder, a mixer of pulp/water, and one or more centrifuges (Kimball 1999).

1.3.3 *Material and Energy Balances*

The principles and techniques of material and energy balances of chemical engineering are, in general, applicable to most food process calculations. However, food processes require special attention, due to the complexity of food materials and the importance of food quality. In material balances, accurate food composition data are difficult to obtain, due to variability even for the same food material. Variations are due to the variety, growing conditions, and age of the raw materials. If reliable experimental data are not available for the food material being processed, approximate values can be obtained from the literature, e.g., the USDA food composition data (Watt and Merrill 1963; Souci et al. 1981).

Simple material and energy balances can be performed on mechanical and heat preservation operations. Simultaneous heat and mass transfer operations, such as drying, blanching, baking, and steam injection, may need more detailed analysis and experimental verification of the assumptions on food composition and energy requirements (Farkas and Farkas 1997). Due to variability of raw food materials, material and energy balances may be required periodically, during the operation of the food processing plants.

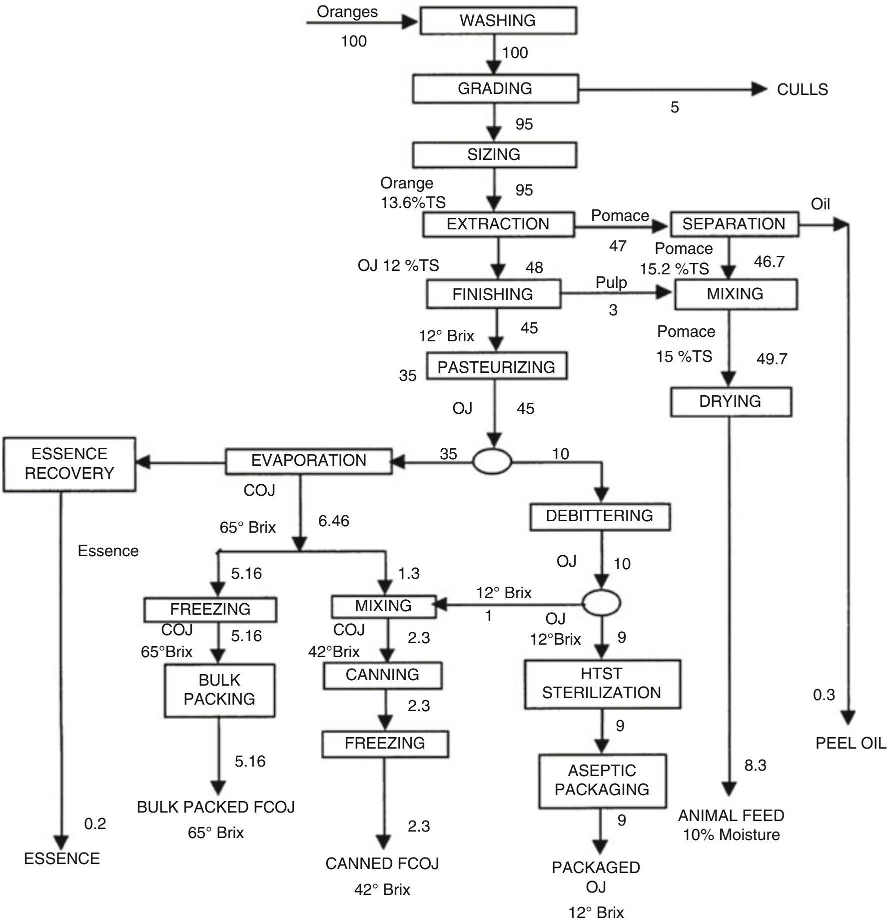


Fig. 1.7 Simplified process block diagram for multiproduct orange processing plant. Basis of material balances: 100 parts of oranges; see Example 1.1. *OJ* orange juice, *COJ* concentrated orange juice, *FCOJ* frozen concentrated orange juice, *CULLS* damaged fruit, unfit for processing

Overall and component material balances are calculated at the boundaries of a food process, from the mass conservation equations in the system:

$$\text{total mass in} - \text{total mass out} = \text{total mass accumulated} \tag{1.14}$$

$$\text{total component in} - \text{total component out} = \text{total component accumulated} \tag{1.15}$$

For continuous operations, the accumulated materials (total and component) are equal to zero.

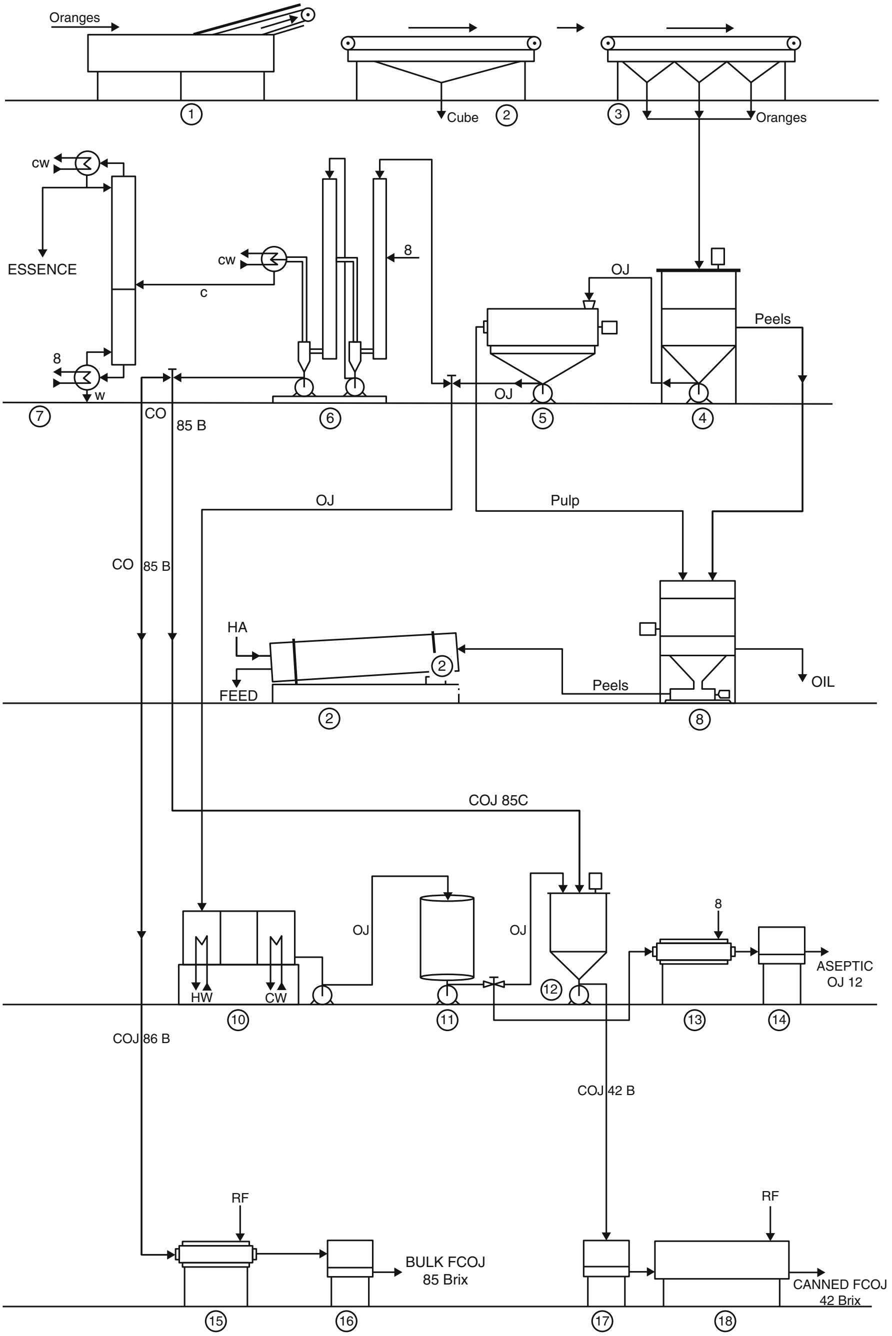


Fig. 1.8 Simplified process flow diagram (PFD) for a multiproduct orange processing plant (see Fig. 1.4)

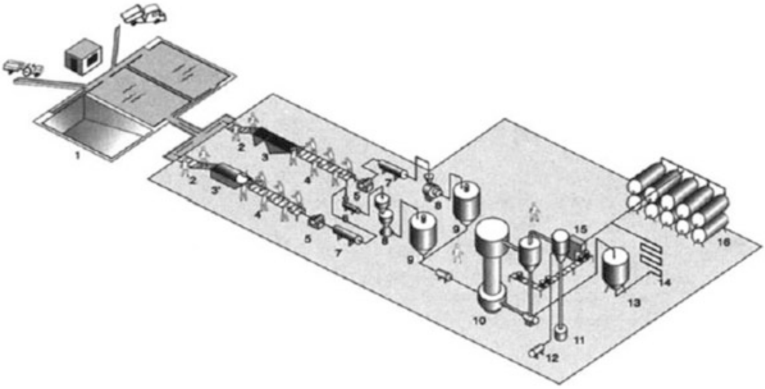


Fig. 1.9 Simplified 3D PFD for a tomato paste processing plant (see Fig. 1.10)

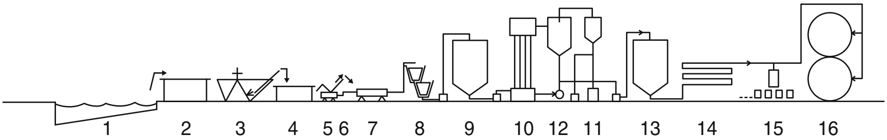


Fig. 1.10 Simplified process flow sheet of the tomato paste processing plant (Fig. 1.9): (1) Water basin, (2) preselection and loading, (3) washing, (4) sorting, (5) crushing, (7) heating, (8) straining of pulp, (9) preliminary storage, (10) evaporator, (11) barometric condenser, (12) vacuum pump, (13) concentrates tank, (14) sterilization, (15) aseptic packaging, (16) aseptic storage

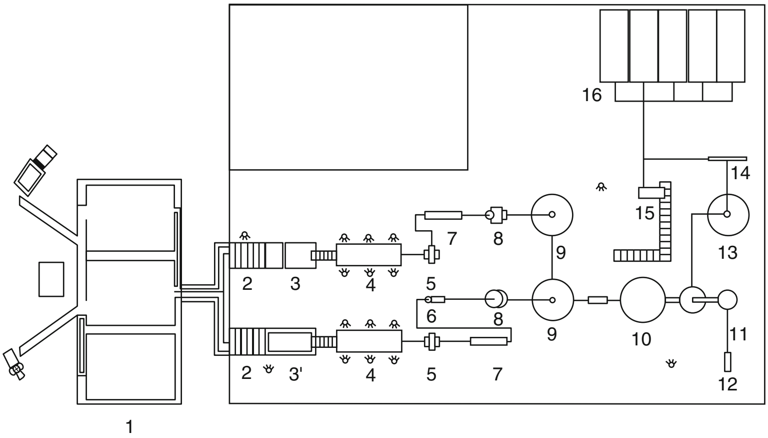


Fig. 1.11 Floor plan (layout of equipment) of a tomato paste plant (see Fig. 1.10)

The component material balance (Eq. 1.15) can be written for one or more food components, which are important in a given processing operation. Typical components, involved in food processing, are water (moisture), total solids (TS), soluble solids (SS), fat, oil, salt, and protein. The soluble solids are usually expressed as °Brix (% sucrose by weight), measured with refractometers, which are used widely in the laboratory and the processing plant. The concentration of components is expressed as mass or weight fraction $x_i = \%(\text{weight})/100$.

Volumetric flows, e.g., L/h or m^3/h, should be converted to mass flows, e.g., kg/h or tons/h, using the density of the material (kg/L or kg/m^3).

Energy balances are calculated at the boundaries of a food process, from the energy conservation equation (first law of thermodynamics) in the system:

$$\text{total energy in} - \text{total energy out} = \text{total energy accumulated} \tag{1.16}$$

For preliminary design calculations and equipment sizing, the main energy form considered is heat and only heat balances are calculated. The mechanical and electrical requirements for pumping, transportation, refrigeration, and operation of the various pieces of process and utility equipment are considered in the detailed process, equipment, and plant design.

Heat balances involve the enthalpy and specific heats of the various process and utility streams. Thus, the total heat of a stream (Q) is equal to the sensible (Q_s) and latent (Q_l) heats:

$$Q = Q_\mathrm{s} + Q_1 = \sum m_\mathrm{t} C_\mathrm{pi} \Delta T + \sum m_j \Delta H_j \tag{1.17}$$

where components i participate in sensible heating or cooling by ΔT degrees (°C or K) and components j are involved in evaporation (condensation) or freezing (fusion). The specific heat of water (C_p) is normally taken as equal to 4.18 kJ/kg, while all food materials have lower values. The heat of evaporation or condensation of water depends on the pressure. Thus, at atmospheric pressure ($P = 1$ bar, $T = 100$ °C), $\Delta H = 2257$ kJ/kg. The heat of freezing or fusion of water is taken as $\Delta H_\mathrm{f} = 333$ kJ/kg.

Thermophysical and thermodynamic data for foods are obtained from food engineering and food properties handbooks and databases (Rahman 2009; Rao and Rizvi 1995; Saravacos and Maroulis 2001). The importance of transport properties in food process and equipment design was discussed by Saravacos (2000). Typical physical properties are given in Appendix B.

The material and energy balances are essential in the design of food processes, processing equipment, process utilities, and waste treatment facilities, in process optimization and control, and in cost analysis of the process and the processing plant. The sizing, design, and selection of food processing equipment are discussed in Chap. 2.

Detailed material and heat calculations are given in Example 1.1.

1.3.4 Computer-Aided Food Process Design

Adoption of computer packages of CAD, used in chemical engineering, is difficult, due to the diversity of food processes and food products and the limited available data on the physical and engineering properties of food materials (Saravacos and Kostaropoulos 1995, 1996). There is a need for more reliable data, especially on the transport properties of foods, which are required in the design of food processes and processing equipment (Saravacos and Maroulis 2001).

In food process design, rough models, which realize their limitations, are more practical than sophisticated computer models and simulations based on uncertain assumptions and data. Computer modeling has been applied to various food processes (Saguy 1983; Teixeira and Shoemaker 1989; ICHEME 1992; Cadbury 1992). CAD is useful in food process modeling and product development (Datta 1998). A generalized CAD package, including mathematical and simulation operations (MATLAB and SIMULINK), has been proposed for design and optimization of food processes (Diefes et al. 1997). The use of computer spreadsheets in food technology is discussed by Singh (1996). Food process modeling, with special attention to food quality and food safety, is discussed by Irudayaraj (2001) and Tijskens et al. (2001).

Process simulators, developed for food processing operations, include the following: (1) belt dryer for food products (Kiranoudis et al. 1994), (2) pasta dryer (de Cindio et al. 1994), (3) aseptic thermal processing (Skjoldebrand and Ohlsson 1993), (4) food process simulator for training production operators (Skjoldebrand et al. 1994), and (5) milk heating simulator under fouling conditions (Georgiadis et al. 1997).

Computational fluid dynamics (CFD), applied to various engineering problems, can be used in the design and evaluation of fluid flow and heat and mass transfer problems of food processing and storage (James 1996).

Computer-integrated manufacturing (CIM) is intended to improve the business and process functions, including both operational and organizational activities (Parrish 1990; Swientek 1993; Downing 1996). CIM enables manufacturers to plan production resources efficiently, based on market forecasts (Edgar 2000; Mermelstein 2000). CIM software can help food companies to schedule personnel, equipment, and utilities and allocate optimal use of their manufacturing lines.

1.4 Food Plant Design

The principles of chemical process and plant design, reviewed in Sect. 1.1, find applications in the design of new food processing plants. The same stages of process and plant design are used, i.e., the preliminary design, the detailed design, the construction of buildings and utilities, the installation of equipment, and the plant start-up (Dolezalek and Wamecke 1981; Wagner 1998).

Although CAD is applied widely in chemical processing, food applications are rather limited, due to the complexity and large variety of food products, processes, and equipment. Some old-fashioned processing methods are still used effectively, and innovations should be examined thoroughly before large industrial application. Mathematical modeling, simulations, and process control in food processing are as good as the underlying physical principles and the technical data available (Clark 1997a).

The selection of a competent and experienced plant designer is essential for the success of the project. The choice between a "turnkey" design of an outside firm and a joint designer-company team depends on the availability of qualified engineers within the company. Criteria of selection of a plant designer are given by Okun (1989) and Aggteleky (1987).

The motivation for plant design may be related to internal or external factors. Internal (company) motivations include problems related to plant site and location, condition of equipment and plant facilities (service life), storage inadequacy, and production statistics. External factors include marketing and economics, food and environmental legislature, competitiveness, know-how and patent acquisition, company acquisition or merging, international markets, and unexpected events.

1.4.1 Elements of Food Plant Design

1.4.1.1 General Aspects

Construction and renovation of food processing facilities is governed by many local, state, federal, and international agencies with overlapping regulations (Popham 1996). Product quality and shelf life are directly affected by the quality of the processing space. Production time can be minimized and sanitation and maintenance programs can be minimized with construction that satisfies regulatory and inspection programs. In addition to food safety (Hazard Analysis Critical Control Point, HACCP), environmental regulations should be considered.

Laws and regulations cover a wide range of constraints, which should be considered at the design stage of a food processing plant. In the USA, such regulations are contained in the FDA Act, the USDA Meat Inspection Act, the GMPs, the 3-A Standards, the Pasteurized Milk Ordinance, the Occupational Health and Safety Act (OHSA), the Environmental Protection Act (EPA), and so on.

The general organization of food processing plants is similar to the setup of other manufacturing companies. The basic departments of a food processing facility are (1) delivery, (2) temporary storage of raw materials, (3) storage of other materials used in food processing, (4) processing, (5) product storage including cold rooms, (6) utilities, (7) effluent treatment, (8) laboratory and R&D, (9) offices, and (10) employee facility rooms.

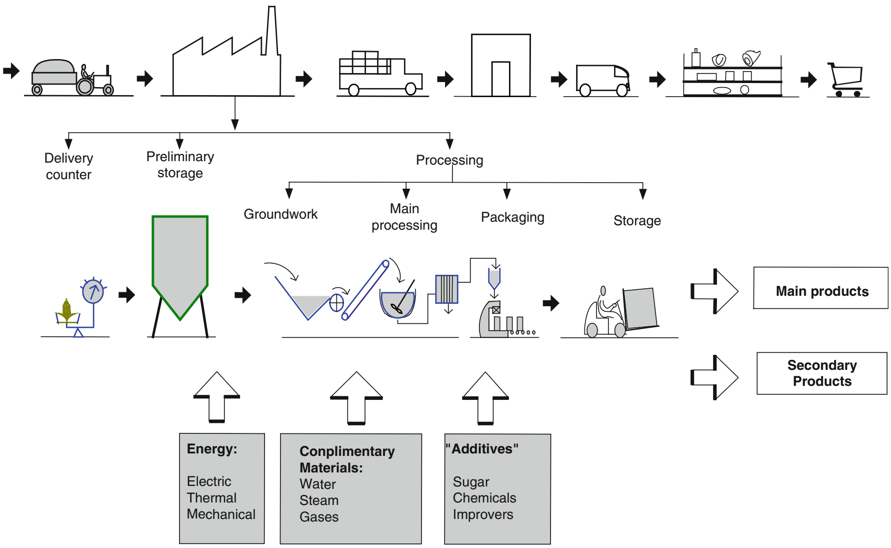


Fig. 1.12 Processing operations of manufactured food

Process flow sheets, discussed in Sects. 1.1 and 1.2, are utilized in the design of equipment and utilities and in plant layout. Proper plant layout is essential for efficient operation, food safety, and effective plant and equipment maintenance (Schwecke 1989; Sinnott 1996). Figure 1.12 shows a food processing flow sheet.

The design of food plant utilities (steam, water, electricity, air, and waste treatment) is similar to the chemical process industries. A summary of typical utilities for food processing plants is given in Appendix D.

There are certain important features that distinguish food-related plant designs and investments from other industrial applications. Some characteristic features are the following:

1. The raw materials and final products of the food industry are sensitive biological materials, which impose certain limits on the processing operations, e.g., temperature and mechanical energy. Raw materials can be stored for a limited time, sometimes under controlled conditions.
2. In several processes, the quality of the final food product depends strongly on a single critical step, which should be performed under the gentlest possible conditions. There is a limit to storage time, after which food spoilage will take place.
3. In many plants, large quantities of sensitive raw materials must be processed in the shortest possible period. Therefore, in the case of seasonal crops, the equipment must be able to withstand sudden extreme processing conditions.
4. Hygienic factors play an important role not only in the food plant but also in the process–food product–operating personnel interaction.

5. The quality of a special product (individuality) should be maintained, even in mass production.
6. In many cases, such as fruits and vegetables, food processing is seasonal. In such operations, a significant part of the employees are unskilled labor.
7. Since most seasonal raw materials are perishable, relatively short-term cash flow must be provided for their purchase.

Plant design refers either to the construction of new processing/manufacturing plants or to the improvement or expansion of existing/operating plants. In the latter cases, a detailed evaluation of the existing operation is necessary, before any commitments are made. The adopted solutions should be introduced into the plant as smoothly as possible, without disturbing the existing operation.

Improvement of an existing plant is an ongoing continuous process, while process, equipment, and plant expansion is a periodic process. Both improvement and expansion may refer to construction of buildings, installation of equipment, or changes in personnel.

Reasons for investments related to the extension or improvement of food industries are (1) increase of capacity or productivity, (2) reduction of the cost of production, (3) environmental issues, and (4) external economic and political decisions.

Reasons for investment in new processing establishments of an already existing enterprise are, among others, (1) extension of activities, (2) meeting of an increased demand, and (3) benefits of new technologies.

Most investments (70–75 %) for food processing plants in the USA (Young 2000) and in Germany (BEV 2000) are related to plant renovation and expansion, and only 25–30 % involve construction of new plants. Renovations and expansions enable to respond to market alternations and requirements faster and with incremental capital investments, combined as well with less investment risk (Gregerson 2001).

Plant design can be divided into two general types: (1) long-term design, applied to new manufacturing lines of the same or new products; it may also be applied in a step-by-step renovation of a process or a whole plant; and (2) short-term design, which aims at meeting and solving urgent problems, such as replacing existing processes or equipment.

In all types of food plant design, the main goal is the achievement of the best possible results with respect to quality requirements, high productivity, and low cost. Some typical requirements of food processing operations and equipment are the following:

1. *Production rate*. In principle, processing should be as fast as possible, in order to reduce the danger of microbial spoilage and infection and prevent quality degradation, e.g., vitamin loss due to prolonged heat treatment. However, the production rate should keep step with the minimal requirements of the applied process, e.g., time–temperature requirement.

2. *Heat application*. In most cases, heat must be applied at the lowest possible level to prevent quality losses. However, in cold chains (refrigeration storage and transport systems), temperature should be kept at the highest possible level for saving energy.
3. *Standardization*. In general, standardization is applied to simplify processing and control operations. However, in several applications, standardization must not have negative effects on the quality and the "individuality" of the food products.
4. *Sanitation*. Hygienic (sanitary) conditions must cover the entire manufacturing spectrum, from raw material lines to final products, covering processes, equipment, buildings, and personnel.

1.4.1.2 New Food Plants

Continuous operation of food processing plants is desirable, since it is more cost effective, particularly in large plants, and the processes can be controlled more effectively. However, batch processing is still practiced in several food plants, due to the complexity of some processes and the diversity and low volume of the processed products. The output of a batch food processing plant can be maximized by judicious plant design, which optimizes the use of the available equipment (Cadbury 1992). Batch processing requires intermediate storage tanks for further processing of the materials (Sinnott 1996). Optimization of the process cycles should consider the entire plant operation. Time-utilization (Gantt) charts should include both processing and cleaning of the process equipment.

Plant layout is particularly important in food processing because of the uniqueness of processes and the strict requirements for food hygiene and product quality. One-story (ground-level) buildings are generally preferred, while multilevel installations are advantageous, when gravity flow of large-volume materials is important, as in grain milling plants.

In planning a new food plant, several factors should be considered, including the following basic requirements: location, product/process, food hygiene (sanitation), plant safety, and flexibility.

1. *Location*. The right choice of plant location is important for present and future processing operations. Plants processing large quantities of raw materials (e.g., sugar beets) into products to be shipped to distant markets must be located near the agricultural production. Plants using large quantities of imported raw materials (e.g., oilseeds) must be located near sea harbors. Plants processing products of short shelf life, like fresh milk, must be located near consumption centers (large cities). Other important factors, determining plant location, are land cost, transportation facilities, climate, water supply, legislation, taxation, and regional infrastructure.
2. *Product/process*. The physical state of the raw materials and products (liquids or solids) affects decisively plant design. Thus, gravity flow of the materials can be utilized in processing liquids and grains. In planning a dehydration plant,

low-humidity packaging and storage areas are needed, while high humidity is needed in packaging and cold storage of ready-to-eat vegetables and fruit salads.

3. *Food hygiene*. Hygiene (sanitation) is a fundamental requirement of all food plant operations: processing, packaging, storage, buildings, and personnel. Microbial and nonmicrobial contamination should be prevented by proper design and operation of all processing equipment and the entire plant. Most of the sources of contamination are related to the processing equipment, and the hygienic design of equipment is discussed in Chap. 2 (Jowitt 1980). Hygienic operation of the whole food plant is discussed in the Sect. 1.4.2.
4. *Plant safety*. Safety of personnel, products, and plant facilities (hazardous operations, HAZOPS) should be considered in any plant design. In respect to the use of food processing equipment, it should be also taken into consideration the recommendations set by organizations engaged in the publication of standards for the hygienic design and the hygienic design and satisfaction of such equipment (e.g., the EHEDG, the European Hygienic Equipment and Design Group). Furthermore, there are specific requirements, recommended by various organizations, for fire hazards, electric motors, dust explosions, and so on. Dust explosions are particularly important in processing and storage of food powders. Moisture-proof electric motors must be used in damp environments, such as canning. Explosion-proof electric motors should be used for dusty environments, such as grain mills and powder conveyors.

   Steam boilers should be located in a separate boiler house to confine any explosion hazard. Plant layout and construction should prevent accidents by the personnel, e.g., special floor coatings and protective rails in silos.

   The noise level in the processing areas should not cause health problems in the operators. Maximum noise levels, according to Directive 86/188 of the European Union, should not exceed 90 dB in 8-h work and 93 dB for 4-h work near the noisy equipment. In some processing areas, the noise level may be excessive, e.g., 90–110 dB in a bottling plant. In such cases, the operators must take protective measures such as wearing earmuffs.

   Noise can be reduced by proper selection of equipment, better foundations and seating of equipment with moving parts, gentle conveying, and isolation of noisy equipment in special rooms.
5. *Food storage*. Storage facilities are influenced by the type of raw material, process, and product. For example, bulk storage and hydraulic transport are used in tomato and orange processing, while silo storage and pneumatic transport are practiced in grain processing. The "just-in-time" delivery policy may reduce significantly the logistic cost and storage space requirements. Surge tanks for temporary storage may be needed in some cases, for the smoother operation of several processing lines.
6. *Flexibility*. In some food plants, the processing operations must be modified according to the nature of the raw materials. Adjustment of equipment and operating lines should be made without disrupting the whole operation and losing valuable time. Plant design should account for periodic cleanup of processing equipment in order to maintain efficiency and hygienic conditions.

1.4.1.3 Plant Improvement

Improvement or adjustment of existing plants is a continuous task in food manufacturing plants. Even newly designed food plants may need improvement, since a perfect design, particularly in food processing, is an impossible task. The difficulties in plant design are manifested especially in seasonal processing, e.g., of fruits and vegetables. In some cases, the same processing facility may be used for processing of different food products, such as thermal processing of fruit/vegetable juices and milk.

Plant improvements may include the following:

1. *Production*. Food quality and plant productivity may be improved through new and better processing methods and equipment.
2. *Conveyance*. Increasing the speed of conveyance/transportation of raw material and products will reduce losses through spoilage and mechanical injury.
3. *Storage*. Better storage facilities and conditions will reduce quality losses and minimize logistic costs.
4. *Energy*. Reduction, e.g., of heat losses by insulation of equipment and control of electrical losses.
5. *Buildings*. Better use of building space and insulation of buildings.
6. *Environment*. Utilization of specific environmental conditions, e.g., low air temperature in potato storage. Elimination or reduction of environmental burden of water effluents, air pollutants, solid waste, thermal pollution, and noise.
7. *Management*. Greater effectiveness in all fields of the enterprise. Improvement of information flow through the various departments and feedback adjustments, using computer technology. Labor conditions could be improved, and the total number of personnel is reduced by judicious automation.

Plant improvement is based on a thorough analysis of the existing plant and in finding alternative solutions of the recognized problems. The consequences of proposed changes must be considered carefully, before any plant alterations are made. Most improvements require “individual” or “custom-made” solutions, in which the expertise and experience of the plant designer are of paramount importance.

1.4.1.4 Plant Expansion

Expansion of existing plants is necessary to meet increased demand of the company’s products or to expand the activities to related new fields. The difference between new plant construction and plant expansion lies in the fact that, in the latter case, the existing substructure of the enterprise is taken into consideration. In planning plant expansion, the following points should be considered:

1. Avoid causing problems to existing installations (e.g., energy and effluent networks), transport systems, or creating production “bottlenecks.” Typical

examples of the last problem are packaging machines and storage facilities, which are designed to be used also in the plant expansion.

2. Use existing installations and equipment for the purpose of reducing investment and operating cost of the expanded facility.
3. Purchase, if possible, the same type of equipment, if similar products are to be produced. In this manner, maintenance cost will be reduced.
4. Purchase new equipment whose combination with existing similar machines will increase plant flexibility. For example, new small compressors, combined with existing larger units, will meet the additional refrigeration load of expanded cold storage facilities.

1.4.1.5 Mobile Food Plants

Mobile food plants may be used in special food processing operations, as in the introduction of a new process (pilot plant), or in seasonal food processing of small food operations (Kostaropoulos 2001). A mobile plant consists of a number of small processing units, usually mounted on a trailer truck, which can be transported to the site of food processing and connected to process utilities (steam, water, refrigeration).

Mobile factories are particularly attractive for processing relatively small quantities of similar raw materials, which are harvested at different seasons and locations, e.g., apricots (summer) and peaches (fall). Large food processing plants have to transport the raw materials, sometimes over long distances. A special type of mobile food plants is the fish-processing ship factories, which move to various fishing areas (Kostaropoulos 1977).

Mobile pilot plants may be used before the construction of the industrial plant for demonstration and for production of test samples of the food product. A preassembled aseptic processing system, installed on a 12-m van platform, was used for test production of fruit and vegetable juices and sauces (Rice 1987). Other mobile food plants, reported in the literature, are portable units for processing of milk, meat, pasta, or bread (Anonymous 1993) and mobile slaughter and meat processing units for pigs (Viere 1994).

1.4.1.6 Advanced Food Plants

New food processing and manufacturing concepts, food structure engineering, process design and control, and hygienic aspects are the elements of advanced modern food plants (SIK 2001). Progress in food processing can be accelerated by adopting new technologies from other processing and manufacturing industries.

Automatic control of food processes can be achieved by combining modern analytical techniques (optical/color, microwave, X-rays), interfacing with computers. Future plants should be able to adjust their production by taking into consideration the consumers' sensory and texture evaluation of the food products.

Total automation of food processing plants, using robotics and computer technology, can prevent microbial contamination and improve hygienic operation and product safety.

1.4.2 Good Manufacturing Practices

1.4.2.1 GMPs

The principles and practices of GMPs should be taken into serious consideration in food plant and equipment design (Popham 1996). GMPs are a combination of manufacturing and management practices aimed at ensuring that food products are consistently produced to meet specifications and customer expectations (NZIFST 1999). They are practical rules and recommendations, based on experience, which, when followed in the various food processing operations, will result in safe and high-quality food products (Gould 1994). In the USA, the following agencies have responsibilities regarding food processing plants and processing equipment: the FDA (Food and Drug Administration), USDA (US Department of Agriculture), EPA (Environmental Protection Agency), FTC (Federal Trade Commission), and CS (Customs Service).

Each country has rules and regulations, related to foods, which should be considered carefully, when building or operating a food plant. The European Union (EU) is developing a uniform food legislature for its 14 member countries (as of 2001).

GMPs cover a wide spectrum of manufacturing practices, but the main emphasis is on food plant hygiene (sanitation), while food quality receives the proper consideration (Troller 1993; Marriott 1997).

The Code of Federal Regulations in the USA (Part 110, Title 21) contains the practices that must be followed in food plants, processing foods for human consumption (Gould 1994). These regulations are enforced by the FDA. They are updated regularly and published in the *Federal Register* (Washington, DC). The rules cover the buildings, processing equipment, and personnel of the processing plant. They also cover processing, hygienic, and control operations, receiving, warehousing, shipping, and distribution of the food products.

In the design and layout of food plants, the following aspects related to GMPs should be taken into consideration: (1) single-floor versus multistory buildings, (2) land space for future expansion, (3) waste disposal, and (4) building details (drainage, doors, lighting, ventilation, plumbing). Regulations similar to the GMPs, related to the design of food plants processing meat and poultry, are administered by the USDA.

The hygienic design and specifications of food processing equipment are discussed in Chap. 2.

Both GMPs and USDA require adequate space for equipment installation and storage of materials, separation of operations that might contaminate food (cross-contamination), and adequate lighting and ventilation.

Process utilities (steam, water, and refrigeration) must be placed in separate rooms and the process fluids transported to the processing equipment through overhead piping. Special treatments are needed for plant floors (tiles, polymer resins, and sealed concrete). Epoxy paints are suitable for protection of plant walls and ceilings (Man 1994a, b; Shepard 1981).

Although the major hygienic hazard in food processing plants is microbial contamination, plant design should also provide for elimination of various pests from food areas, such as insects, rodents, and birds.

Plant design should consider cleaning of food processing equipment and buildings, with appropriate preparation room for cleaning solutions and CIP piping.

1.4.2.2 Food Safety Programs and HACCP

Food quality programs are essential in the processing, storage, and distribution to control product consistency. The need for uniform standards in world trade has led to the adoption of international standards, like the series of ISO 9000, which detail the quality assessment procedures for industrial products in general. Food quality usually refers to the nutritional, sensory, compositional, and convenience attributes of food products. Sometimes, food quality includes food safety, which refers to the absence of microbial, chemical, or physical hazards.

Food safety programs are required for securing food safety and for complying with the regulations of government and international organizations. A food safety program consists of documents, records, systems, and practices, including HACCP. Most modern food safety programs are implemented by the HACCP system. The HACCP system was first introduced in 1989 by the US National Advisory Committee on Microbiological Criteria for Foods (Gould 1994). It is a system that identifies, evaluates, and controls hazards that are significant to the production of safe food. HACCP was first applied to meat, poultry, and dairy products, which are sensitive to microbial spoilage and hazards.

The HACCP system is based on the following seven principles (Codex Alimentarius 1997; NZIFST 1999):

1. Conduct a hazard analysis (biological, chemical, and physical).
2. Determine the critical control points (CCPs).
3. Establish critical limits for each CCP.
4. Establish a system to monitor each CCP.
5. Establish the corrective action to be taken when monitoring indicates that a particular CCP is not under control.
6. Establish procedures for verification to confirm that the HACCP system is working effectively.

7. Establish documentation concerning all procedures and records appropriate to these principles and their application.

Prerequisite tasks needed for successful application of the HACCP programs are assembly of the HACCP team, description of the food and its distribution, intended use and consumers of the food, development of the flow diagram which describes the process, and verification of the flow diagram (NACMCF 1997). Computer software is available for performing effective HACCP and food safety surveys (Mermelstein 2000; Mortimore and Wallace 2000, 2001).

Proper plant design is a prerequisite for an effective HACCP program (Kvenberg 1996). Consideration should be given to eliminating or substantially reducing the potential hazards. The following factors are important for effective design: (1) product flow through the processing system without cross-contamination, (2) prevention of contamination of foreign bodies, (3) restriction of employee traffic, and (4) positive air pressure in the processing areas.

1.4.3 Food Plant Economics

1.4.3.1 Overview of Food Plant Economics

The basic aim of economic overview of plant design is to explore the economic implications of plant tasks undertaken. These tasks may be confined to a limited intervention on existing plant operations (e.g., energy savings through additional investment), or quite extended, as estimation of the profitability of a whole investment. Very often, economic analyses comprise comparisons between cash inflow (income) and outflow (expenses), as shown in Fig. 1.13. In plant design, this counteracting relation may be influenced by further opposing interactions, such as when pure economic or socioeconomic factors are involved.

Costs of food plants, e.g., the cost of heat exchangers as a function of the heating area (Sinnott 1996) or the cost of evaporators as a function of the heating area (Fig. 1.1) and the cost of energy (Bernecker 1984), may be linear or nonlinear. Many economic time-related functions are nonlinear, since market changes are unpredictable. Therefore, quite often, economic forecasting may be verified only in a range confined by optimistic or pessimistic prediction curves (Fig. 1.14).

The relation of unit cost as a function of increased production rate is nonlinear. As a rule, the unit cost decreases when the production rate is increased (Kettner et al. 1984). However, the unit cost (y)–production rate (x) curve tends to become asymptotic to the x-axis, due to the additional excessive expenses, required when production capacity reaches its limits.

No perfect prediction of future economic developments can be achieved by mere plant design. This is because, besides economic developments, after some time, changes due to technical progress may make the actual investment unprofitable. These changes may refer to products, processes, and equipment. Good plant design

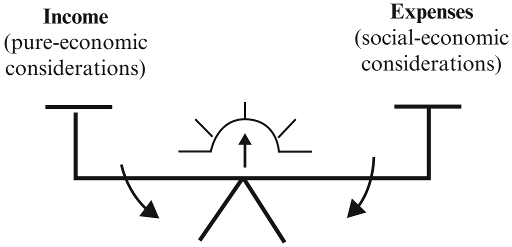


Fig. 1.13 Economic comparisons

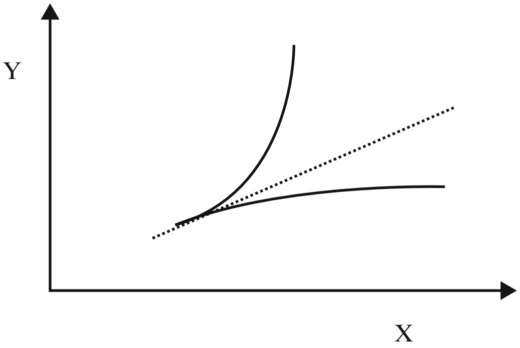


Fig. 1.14 Economic forecasts

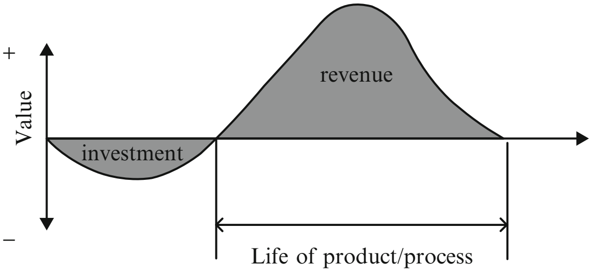


Fig. 1.15 Economic value of an investment

strives to keep processing methods and whole plants in operation as long as possible. Furthermore, the basic aim is to achieve profitability with the less possible changes in the manufacturing process.

The revenue that will be achieved up to the time the actual investment "runs out" must be larger than the needed expenses (Fig. 1.15) (Kettner et al. 1984). The actual investment may refer to expenses for the development and introduction of a new product or a new or improved manufacturing process.

The "breakeven point" (BEP) of an investment indicates the time required for getting back, through sales and so on, the money that was spent for investments of starting the production of a product (fixed expenses) and the money that was subsequently spent up to the time that revenues equalize the total expenses (Fig. 1.3). As mentioned earlier, these two curves may be nonlinear. The BEP curve may be used to estimate the optimal production rate (e.g., pieces per hour) with respect to the production expenses (Aggteleky 1987).

In economic comparisons, the optimum operating point is usually obtained by a graphical representation of the investment and operating curves (Fig. 1.16). As the production capacity (X) is increased, the operating cost per unit product (F_1) decreases and the investment cost (F_2) increases. The summation of the two curves (F_3) goes through a minimum (M), which is the optimum point.

Figure 1.17 shows the critical "breakeven" point (M) as an intersection of the curves for expenses of operation and total income. It indicates the time at which the total income surpasses the expense obligations.

Fig. 1.16 Optimum operating conditions

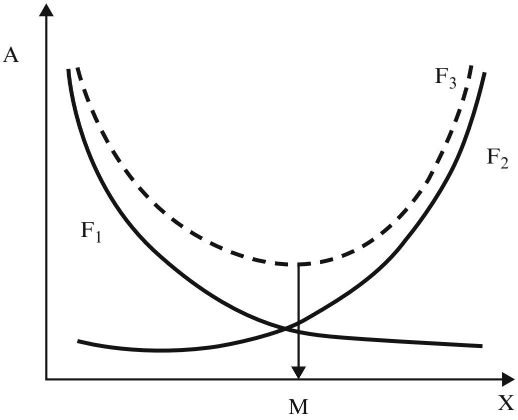
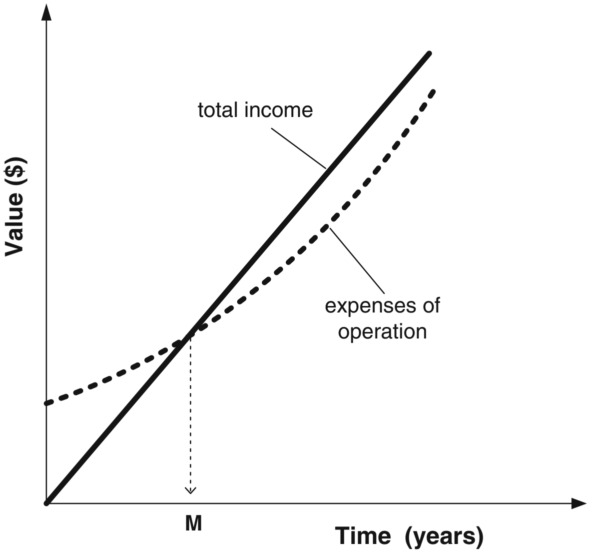


Fig. 1.17 "Breakeven" point of an investment



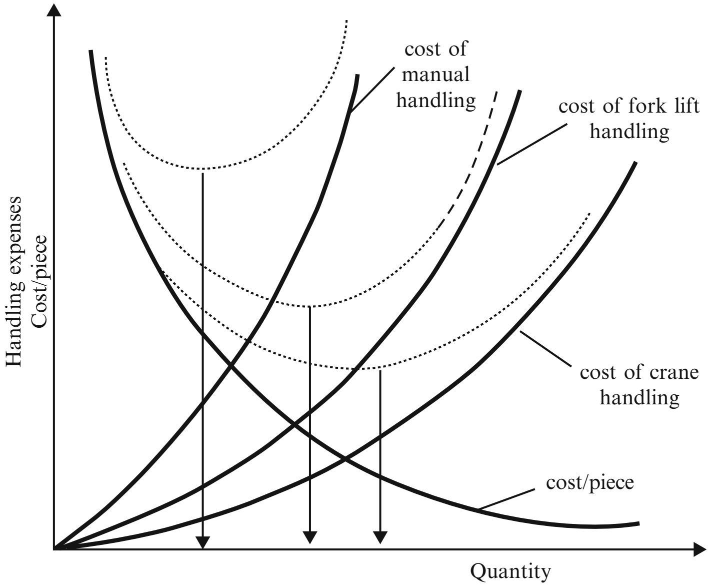


Fig. 1.18 Cost of material handling methods

In food processing, the optimum operating condition is important in finding the optimal investment in energy-related problems, e.g., the optimum number of effects in a multiple-effect evaporator and the thickness of insulation in cold storage rooms. Other examples are the reduction of cost through automation (Aggteleky 1982), the extension of plant design (Kettner et al. 1984), and the money savings through maintenance of equipment.

The optimization method may also be applied to scheduling the various material handling, production, and other plant operations. Figure 1.18 shows the cost of material handling in relation to the method applied and to the quantity transported. Expenses are high when forklifts or cranes are used in handling small quantities or in manual handling of large quantities. As indicated in Fig. 1.18, there is an optimum for each case on material transport (Aggteleky 1982).

Plenty of free space in food processing plants is beneficial up to a certain point. It facilitates material handling, makes temporary storage possible, and simplifies maintenance. However, if certain limits are exceeded, the expense for additional space is unreasonably high, because the cost of buildings, piping, and energy increases and transport distances become too long. Again, the results of a cost–benefit analysis, as presented in Figs. 1.16 and 1.17, can show the optimum space requirements, in relation to the quantity handled and the method applied.

1.4.3.2 Economic Analysis of Food Plants

The economic evaluation of food processing plants is based on the principles of chemical process and plant design: the estimated capital cost includes processing equipment and facilities, buildings, installation, utilities, environmental control, engineering fees, and contingency.

However, there are some basic economic differences between chemical and food industries. One major difference is the fact that the raw materials and the processed products of the food industry cannot, in general, be stored for a very long time. This increases short-term financial obligations, such as payment of raw food materials. Therefore, additional capital is needed for storage of raw materials, processed products, and packaging materials (Clark 1997a, b). Economic analysis requires the estimation of DCFRR and payback period ROI (Eqs. 1.12 and 1.13). The ROI time in the food industry is usually taken as 5 years.

Preliminary plant cost estimation is based on the cost of major processing equipment (see Example 2.1). In the chemical industry, the cost of a plant is estimated as four to five times the cost of the major equipment. However, the cost of the major food processing equipment is relatively higher, because smaller units are used, the materials of construction are expensive (stainless steel, hygienic design), and there is less piping and instrumentation. As a result, the estimated plant cost in food processing is about 1.5–2.5 times the cost of the major equipment (Bartholomai 1987; Pyle 1997).

An empirical rule for total cost of large food plants is USD 1200/m^2 floor space (2000 prices), 65 % of which is for installed equipment and 35 % for buildings (Clark 1997b).

The major part of the operating cost of food processing plants (60–80 %) is for raw materials and labor (Maroulis and Saravacos 2008). The rest is for packaging materials, energy, and depreciation (about 10 % each).

Mathematical modeling and simulation are used to evaluate and optimize the operation of food processing plants. Thus, modeling and linear programming were applied to an apple juice concentrate plant in Argentina (Bandoni et al. 1988). The plant processed 164 tons/day of apples, producing 20.6 tons/day of apple juice concentrate 72° Brix, 1.2 tons/day of aroma essence, and 54.5 tons/day of pomace. Raw material represents 60–65 % of the total cost of apple juice concentrate. Availability of raw material and apple variety has an important effect on process economics.

In processing operations, in which certain equipment is planned to be utilized for a limited period, the salvage value of the replacement of such equipment may also be important. Usually, the amortization of common equipment does not exceed 7–10 years. Besides operational reasons for a limited time of utilization of equipment, replacement of certain equipment before its amortization period may be advisable, when this equipment is surpassed technologically, influencing the overall efficiency of the enterprise, but the equipment still has a salvage value, which is equal to its initial value minus its depreciation.

Some reasons for the depreciation of equipment are (1) relatively low productivity of existing equipment, (2) introduction of new processing methods making obsolete existing equipment, (3) introduction of new systems of automation and computer technology which cannot work with the old equipment, (4) difficulty in getting the right personnel, and (5) increased repairing cost in maintenance.

An economic analysis of a citrus processing plant in Italy was presented by Moresi (1984). The plant processed 20 tons/h of oranges and alternatively 10 tons/h of lemons, producing frozen citrus juice concentrates, peel oil, and dried pomace. The block flow sheet of the plant is similar to Fig. 1.7. The profitability of the citrus plant depends strongly on the cost of raw material (oranges and lemons), which accounts for about 70 % of the total product cost. In order to compete in the world market of citrus concentrate, the raw material may have to be subsidized by the local government or union, e.g., the European Union.

Example 1.1 Calculate preliminary material and energy balances for the simplified PBD shown in Fig. 1.7 and the flow sheet of Fig. 1.8. These diagrams show a medium-sized multiproduct plant, which will process 20 tons/h (20,000 kg/h) of oranges, and it will operate continuously 24 h/day, 25 days/month for 4 months/year (i.e., 2400 h/year). The plant will produce aseptically packaged orange juice (OJ) 12° Brix, frozen concentrated orange juice (FCOJ) 42° Brix in metallic cans, FCOJ 65° Brix in bulk containers, dried animal feed of 10 % moisture, peel oil, and fruit essence. Other by-products from orange wastes, which could be produced in considerable quantities, include citrus molasses, pectin, and flavonoids.

Data on processing and properties of oranges were obtained from the literature on citrus products (Kimball 1999; Ting and Rouseff 1986; Nagy et al. 1993). A similar citrus processing plant with mixed feed of oranges and lemons was analyzed by Moresi (1984).

Material Balances

The oranges fed to the processing plant are assumed to contain 13.6 % TS (total solids) and to yield 48 % OJ 12° Brix, 47 % pomace, and 5 % damaged fruit, unfit for processing (culls). Although the °Brix value refers to % sucrose in aqueous solutions, for preliminary calculations, it can be assumed to be equivalent to % soluble solids (% SS) or % total solids (% TS), by weight.

Material balances are written around each unit operation, according to the basic equations (overall, 1–15, and component, 1–16), assuming continuous operation (no accumulation of material). All balances are based on a feed of 100 parts of raw fruit, which includes 95 % sound fruit and 5 % culls.

Juice extraction. The solids concentration (X) of the orange pomace from the juice extractor is calculated from component material balance, $48(0.12)+47X=95(0.136)$ and $X=15.2$ % TS.

Oil separation. Oil separation by pressing, emulsification, and centrifugation is assumed to yield 0.3 % peel oil, reducing the amount of pomace to 46.7 %, without substantial change of the 15.2 % TS.

Juice finisher. The finisher is assumed to separate the extracted juice into juice of 12 % TS (or °Brix) and 3 % pulp of 12 % TS. Thus, the juice will be 48 – 3 = 45 %. The mixing of 3 % pulp and 46.7 % pomace will yield 49.7 % pomace with a concentration X, calculated from the balance equation, $49.7X = 46.7(0.52) + 3(0.12)$ and $X = 15$ %.

Drying. The orange pomace is dehydrated in a rotary air-dryer into dried pellets for animal feed. Assuming a moisture content of 10 % and no losses of solids, the animal feed will be 49.7(0.15)/0.90 = 8.3 %.

Pasteurizing. All 12° Brix OJ is pasteurized at 90 °C for 10 s to inactivate the pectic enzymes, which may damage the cloudy juice. There is no change of material balance in this operation. It should be noted that the OJ directed to the evaporator may not be pasteurized, if processed fast enough (no delay), since the first effect of the evaporator usually operates at relatively high temperature (e.g., 90 °C or higher).

Splitting of orange juice. The pasteurized 12° Brix OJ is split into two streams; one part (35 %) is used for production of COJ and the rest (10 %) for production of packaged single-strength and "cut-back" OJ. The split (35/10) is arbitrary, but in practice it is dictated by the demand of juice products. Different products could also be produced, e.g., chilled OJ.

The 10 % pasteurized OJ is debittered to remove traces of the bitter flavors (limonene and naringin). Debittering is accomplished by passing the OJ through an ion-exchange column, which is regenerated and reused several times. The debittered OJ is split into two parts, one (9 % of the total oranges) for aseptic packaging and the rest (1 %) for mixing with the 65° Brix COJ (cut-back juice). No significant change of OJ flows takes place in the debittering operation, since the bitter components removed (limonene and naringin) are present only in parts per million concentration.

Evaporation. A multiple-effect (in this example, three) evaporator of the long vertical tube type is used for the evaporation of the 35 % OJ into 35(0.12)/0.65 = 6.46 % COJ 65° Brix.

The amount of water evaporated from the 35 % OJ will be 35 – 6.46 = 28.54 %.

Mixing (*cut-back*). A quantity (X) of 65 % COJ is mixed with 1 % of "cut-back" OJ to produce $(1 + X)$ % COJ of 42° Brix, according to the equation $(0.65)X + (0.12)1 = (0.42)(1 + X)$ and $X = 1.3$ %. Therefore, the amount of the 42° Brix COJ will be 1.3 + 1 = 2.3 % and, of the 65 % COJ, 6.46 – 1.30 = 5.16 %.

Essence recovery. Since a triple-effect evaporator is used, the condensate of the first effect will be approximately 28.54/3 = 9.5 %, which is assumed to contain all of the volatiles of the orange juice, and it is used as the feed to the essence distillation column. For essence recovery 0.2 % on the raw oranges, the essence concentration in the column will be 9.5/0.2 = 47.5-fold, and the overall concentration of the fruit essence will be 47.5 × 3 = 142.5-fold (based on the raw oranges).

Final operations of juices. The aseptic packaging of the OJ and the freezing-packaging operations of the concentrated juice do not change appreciably the compositions and amounts of the materials.

Material balances for 20,000 kg/h of oranges: 12° Brix OJ, 20,000 × 0.45 = 9000 kg/h. Pomace 15 % TS, 20,000 × 0.497 = 9940 kg/h. 12° Brix OJ for concentration, 20,000 × 35 = 7000 kg/h.

Packaged 12° Brix OJ, 20,000 × 0.09 = 1800 kg/h. Total 65° Brix COJ, 20,000 × 0.0646 = 1292 kg/h.

Packed 65° Brix FCOJ, 20,000 × 0.0516 = 1032 kg/h.

Canned 42° Brix FCOJ, 20,000 × 0.023 = 460 kg/h.

Water evaporated in evaporator, 20,000 × 0.2854 = 5708 kg/h.

Feed to essence recovery column 5708/3 = 1900 kg/h.

Concentrated (distilled) essence,

$$20,000 \times 0.002 = 40 \text{ kg/h.}$$
$$\text{Dried orange pomace}, 20,000 \times 0.083 = 1660 \text{ kg/h.}$$
$$\text{Peel oil}, 20,000 \times 0.003 = 60 \text{ kg/h.}$$

Heat Balances

The material flows obtained from material balances are utilized in energy balance calculations. For preliminary calculations of equipment sizing and process economics, the heat balances are the most important, and they can be estimated on the PBD. Mechanical and electrical energy, refrigeration, and fuel calculations require more details of the processing equipment and typical numerical examples are given in subsequent chapters of this book.

Calculation of heat balances around each processing unit requires thermophysical data, particularly specific heats, enthalpies, and densities of the process streams. For this example, the specific heats (C_p) of orange juices were obtained from Kimball (1999). They are very close to the C_p of aqueous sucrose solutions: 12° Brix (OJ), 3.86 kJ/kg K; 42° Brix (COJ), 3.06 kJ/kg K; and 65° Brix (COJ), 2.44 kJ/kg K.

The specific heat of the orange juices decreases slightly with decreasing temperature down to the freezing point. For preliminary analysis, the specific heats of unfrozen juices are considered constant. The effect of freezing can be taken into consideration by using the heat of fusion (or freezing) of water, which is $\Delta H_f = 333$ kJ/kg. Empirical equations for the prediction of the thermophysical properties of orange juices are given by Kimball (1999).

Steam requirements. Steam is used for evaporation, pasteurization, and sterilization. Assume that saturated steam of 100 % quality at 110 °C (1.43 bar absolute pressure) is to heat the first effect of the evaporator. The heat of vaporization (or condensation) of water at 110 °C is $\Delta H_v = 2230$ kJ/kg (Smith and Van Ness 1987). The theoretical steam economy (kg of evaporated water/kg steam) for the triple-effect evaporator is close to 3 (see Example 7.1). However, in practice, the steam economy (E) would be lower, and for a triple-effect evaporator, assume

$E = 2.5$. Thus, the steam requirement for evaporating 5708 kg/h of water will be $5708/2.5 = 2283$ kg/h.

The condensate from the first effect of the evaporator (at 110 °C) is used to preheat the feed of orange juice to the evaporator.

Steam requirement for the essence recovery column: The feed enters the column as a saturated liquid and the rate of $F = 1900$ kg/h. The distillate is $D = 20{,}000 \times 0.0002 = 40$ kg/h and the residue $B = F - D = 1900 - 40 = 1860$ kg/h (see Chap. 11). Assume a practical reflux ratio of $R = 2$, i.e., $L/D = 2$. Therefore, $L = 2D = 2 \times 40 = 80$ kg/h, and $V = 80 + 40 = 120$ kg/h (L, V, and D are the flow rates in the enriching section of the column). For the stripping section of the column, $L' = F + \mathrm{L} = 1900 + 80 = 1980$ kg/h, and $V' = L' - B = 1980 - 1860 = 120$ kg/h. The steam (110 °C) required in the reboiler of the distillation column will be approximately equal to the flow rate of vapors in the stripping section, i.e., $S = V' = 120$ kg/h. The column is assumed to operate at atmospheric pressure with a practically constant boiling point of 100 °C.

Steam requirements for pasteurization and sterilization, using 1.43-bar steam (110 °C): Pasteurization of 9000 kg/h 12° Brix OJ by heating from room temperature (assume 20 °C) to 90 °C requires steam (X, kg/h), obtained from the equation, $X = [(9000)\ (3.86)(90 - 20)]/2230 = 1090$ kg/h. For sterilization of 1800 kg/h 12° Brix OJ at 95 °C for 15 s, steam requirement $[(1800)\ (3.86)\ (95 - 20)]/2230 = 202$ kg/h.

Total steam requirement is 3695 kg/h.

The air-dryer of the animal feed will use a fuel (e.g., gas) as a heat source, since steam is not economical for this product and flue (combustion) gases of high temperature can be tolerated for this product (see Example 8.1).

Cooling water. The major requirement for cooling water is to condense the water vapors of the last effect of the evaporator. Assume that the vapors in the last (vacuum) effect condense at 50 °C (see Example 7.1) and that cooling water at 20 °C is used. The heat of condensation of water at 50 °C is $\Delta H_v = 2384$ kJ/kg, and the required water will be $[(1900)(2384)]/[4.18(50 - 20)] = 36{,}121$ kg/h.

The essence column operates at atmospheric pressure, condensing the vapors ($V = 120$ kg/h, mainly water) at 100 °C ($\Delta H_v = 2257$ kJ/kg), without subcooling. Cooling water requirement: $(120)(2257)/[4.18(100 - 20)] = 810$ kg/h.

Total cooling water requirement: $36{,}121 + 810 = 36{,}931$ kg/h or about 40 m^3/h.

The cooling requirements of the pasteurizer and sterilizer are neglected (heat regeneration).

Summary of material and energy balances of Example 1.1

Raw material: 20,000 kg/h oranges (13.6 % TS)
Products: Packaged orange juice (OJ) 12° Brix, 1800 kg/h
Canned frozen concentrated (FCOJ) 42° Brix, 460 kg/h
Packed frozen concentrate (FCOJ) 65° Brix, 1032 kg/h
Dried orange peels (pomace) 10 % moisture, 1660 kg/h
Peel oil, 60 kg/h
Fruit essence 40 kg/h

Steam requirements: evaporation	283 kg/h
Essence recovery	120 kg/h
Pasteurization	1090 kg/h
Sterilization	202 kg/h
Total steam	3695 kg/h

Fuel requirement for drying: 485 kg/h LPG (Example 8.1)

Cooling water: condenser of evaporator	36,121 kg/h
Essence recovery column	810 kg/h
Total cooling water	36,931 kg/h

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