Christopher G.J. Baker *Editor*

Handbook of Food Factory Design

Springer

Handbook of Food Factory Design

Christopher G.J. Baker
Editor

Handbook of Food Factory Design

Springer

Editor
Christopher G.J. Baker
Chemical Engineering Department
College of Engineering and Petroleum
Kuwait University
Kuwait

ISBN 978-1-4614-7449-4 ISBN 978-1-4614-7450-0 (eBook)
DOI 10.1007/978-1-4614-7450-0
Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2013944214

© Springer Science+Business Media New York 2013
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

Food manufacturing has evolved over the centuries from a kitchen industry to a modern and sophisticated operation involving a wide range of different disciplines. Thus, the design of food factories requires a holistic approach based on a knowledge of the natural and biological sciences, most engineering disciplines, relevant legislation, operations management, and economic evaluation. A typical factory includes the food-processing and packaging lines, the buildings and exterior landscaping, and the utility-supply and waste treatment facilities. Design of the production line, the heart of the factory, is in itself interdisciplinary in nature and can involve food scientists; microbiologists; and chemical, mechanical, and control engineers as well as other specialists. The specification and design of the buildings is naturally a civil engineering responsibility but inputs from other members of the design team are essential. Finally, provision of the utilities (e.g., water, steam, electricity, HVAC, and compressed air) and waste treatment facilities requires other specialist engineering input. The project manager has a vital role to play in coordinating all required activities both in the design and construction phases. It is his responsibility to ensure that all tasks are completed on time and within budget.

This Handbook attempts to compress comprehensive, up-to-date coverage of the areas listed above into a single volume. Naturally, compromises have to be made, particularly when attempting to balance breadth versus depth. Thus, many of the topics covered as a chapter herein could and, in some cases have, been the subject of complete books. References to these more comprehensive texts are given in the chapters concerned. Another difficulty is that every country has its own body of legislation covering all aspects of food manufacture. In this work, reference has been made almost exclusively to US, EU, and UK legislation. Information pertaining to other countries is widely available on the Internet, which also enables the reader to keep up with legislative changes. Use of the Internet, however, should not be used as a substitute for sound professional advice in this area.

It is hoped that the Handbook of Food Factory Design will prove to be of value across the food-manufacturing community. It will undoubtedly be of interest to professionals involved in construction projects. The multidisciplinary nature of the subject matter should facilitate more informed communication between individual specialists on the team. It should also provide useful background information on food factory design for a wider range of professionals with a more peripheral interest in the subject: for example, process plant suppliers, contractors, HSE specialists, retailers, consultants, and financial institutions. Finally, it is hoped that it will also prove to be a valuable reference for students and instructors in the areas of food technology, chemical engineering, and mechanical engineering, in particular.

I would like to express my gratitude to each of the authors who has provided chapters for this book. Their knowledge, patience, and professionalism cannot be acknowledged too highly. Special thanks are also due to Campden BRI, Leatherhead Food Research, and the UK Health and Safety Executive who granted permission for their work to be freely quoted and adapted for use in this Handbook.

Al-Khaldiya, Kuwait Christopher G.J. Baker

Contents

Part I Process Considerations

Part II Factory Infrastructure

Part III Utilities and Services

Part IV Project Engineering and Management

Chapter 1
Introduction

C.G.J. Baker

1.1 Introduction

Food and drink are essential to human life. Although basic foodstuffs have remained largely unchanged over the centuries, the availability and choice of different products have increased enormously. This can be attributed largely to the introduction of industrial production techniques. This is clearly illustrated in Lynn Olver's Web site http://www.foodtimeline.org in which she compiled a well-researched and documented history of food from before 10,000 BC to the present. In many cases, today's commonly enjoyed mass-produced foods have evolved from the kitchen to the factory.

It is not absolutely certain which product holds the distinction of being the first to be manufactured in a "modern" food factory. What is certain is that the facility would have been very different from those in operation today. One of the earliest examples listed by Olver indicates that chocolate "bricks" were manufactured on an industrial scale as early as 1764 by a James Baker and a John Hannon in Dorchester, MA. However, in common with many other industry sectors, automation and growth of the food industry did not start to take off until the middle of the nineteenth century. Thereafter, the number of examples has continued to mushroom until the present day.

The present handbook focuses on the design of food factories. This is a multifaceted exercise, which involves a number of disciplines and techno-economic areas as discussed below. It does not describe specific food-manufacturing processes in detail as these have been discussed elsewhere. For example, the 24th edition of Food Industries Manual (Ranken et al. 1997) devotes individual chapters to the following sectors of the food industry: meat and meat products, fish and fish products, dairy products, fruit and vegetable products, cereals and cereal products, fruit juices and soft drinks, alcoholic beverages, fats and fatty foods, salt, acid and sugar preserves, hot beverages, sugar and chocolate confectionery, snack foods and breakfast cereals, and, finally, composite foods and ready meals. Each of these chapters is logically structured so as to give the reader an in-depth overview of the raw ingredients, processing steps, finished products, and quality issues. Food Industries Manual also includes additional chapters covering a variety of topics of general interest to the food industry. Bartholmai (1987) contains a series of chapters that describe in some detail 41 process designs spread across many subsectors of the food industry. These include equipment lists. The principal results are summarized in the Appendix to this chapter. Although the costs are dated, the information presented

---

C.G.J. Baker (✉)
Chemical Engineering Department, College of Engineering and Petroleum,
Kuwait University, P.O. Box 5969 Safat, 13060 Kuwait
e-mail: christophergj.baker@gmail.com

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_1,

can provide a useful starting point in the design of the processes covered. In addition, there are a number of general texts that focus on food-manufacturing technology. Some of the more recent include Saravacos and Kostaropoulis (2002), Smith and Hui (2004), López-Gómez and Barbosa-Cánovas (2005), Barbosa-Cánovas et al. (2005), Sun (2005), Brennan (2006), Ramaswamy and Marcotte (2006), Fellows (2009), and Singh and Heldman (2009). Others are more specialized in their content; for example, drying (Baker 1997), canning (Larousse and Brown 1997), pulsed electric fields (Barbosa-Cánovas and Zhang 2001), high-pressure processing (Doona and Feeherry 2007), and hygiene issues in food factory design (Holah and Lelieveld 2011). A number of texts relating to specific food-processing sectors have also been published, for example, Hui et al. (2003) on vegetable processing and Walstra et al. (2006) on the dairy industry.

Handbook of Food Factory Design is divided into four parts, each of which describes individual aspects of the design and its execution. Part I, which contains Chaps. 2–10, focuses on process issues. Chapter 2, Process Specifications, describes the development of flow sheets and the scheduling of batch processes. It then goes on to consider the fundamentals of mass and energy balancing and their application in food manufacturing. Chapter 3 describes the wide variety of processing equipment employed in food manufacture. It is divided into a series of sections that address individual types of operations, viz., raw materials handling, mixing and emulsification, filtration, centrifugation, extrusion cooking, heat processing, irradiation, food storage, and packaging. Different aspects of the hygienic design of food-processing equipment are described in Chap. 4. This addresses issues relating to materials of construction and the basic principles of design and describes a number of examples of the application of these principles. Chapter 5 provides a comprehensive account of the methods used to move materials both within and to and from the food factory. Guidance as to the selection of an appropriate technique for both solids and liquids is also provided. Productivity issues are considered in Chap. 6. Here, relevant aspects of industrial and operations management, including factory location, plant capacity and layout, and the impact of production scheduling are covered. Chapters 7 and 8 address safety and health and environmental issues, respectively. Chapter 7 examines the principal causes of accidents and risks to occupational health in food manufacturing. It also considers risk assessment in both existing factories and in factories at the design stage. Chapter 8 first describes the principal sources of pollution from food factories. It then goes on to discuss the design and implementation of the ISO Environmental Standards (ISO 14000 series) and Environmental Management Systems. Control and monitoring of food-processing equipment is discussed in Chap. 9, which includes sections on instrumentation, control equipment and strategies, and data management. Finally, Part 1 concludes with Chap. 10, which covers the use of computers as an aid in the design of food factories. This chapter focuses principally on the use of commercial simulation packages and provides several illustrative examples of their use.

Part II, which contains Chaps. 11–13, focuses on the factory infrastructure. Chapter 11, Site Considerations, first addresses site-selection issues. It goes on to address the obvious question as to whether an existing site is suitable for the purpose and, if not, compares brown-field and green-field alternatives. The chapter concludes with a discussion of site and ground inspections. Food factory design principles are discussed in some depth in Chap. 12. Topics include preparation of a preliminary design from a concept brief, site development, movement of material and people, material handling and storage, layout of the factory and other facilities, services, and environmental considerations. Construction techniques and finishes are described in Chap. 13. These include the factory superstructure, roof, walls, floors, doors and windows, and interior features. Also considered are fire detection and protection.

The different utilities and services that are employed in food factories are discussed in Part III (Chaps. 14–18). Steam-raising systems are considered in Chap. 14, which first addresses boiler feedwater quality and treatment issues. It then goes on to describe different boiler designs, boiler and fuel selection, and steam distribution systems. Conventional and more novel refrigeration systems are the subject of Chap. 15, which also addresses the environmental impact of different refrigerants.

This chapter also discusses the specification, design, and optimization of refrigeration systems. Chapter 16 considers the requirements for heating, ventilation, and air conditioning (HVAC) in food factories. It addresses both practical issues and the use of techniques such as computational fluid dynamics (CFD) as design aids. The efficient use of energy (natural gas, steam, and electricity) and water in food factories is discussed in Chap. 17. This chapter also includes an evaluation of cogeneration (combined heat and power systems). Chapter 18 describes the principal technologies employed in the primary, secondary, and tertiary treatment of wastewater produced in food-manufacturing operations.

In conclusion, Part IV of this handbook contains two chapters describing the role of the project engineer in the design and building of food factories. Chapter 19 discusses his/her role in the factory design stage. The cyclic nature of investment cycles is first considered as is the project engineer's changing role as the focus moves from pre-investment studies, through detailed design to contract preparation and tendering. The chapter highlights what is arguably the most important part of any project, namely unambiguous specification of its objectives and deliverables. In the concept stage, all key elements of the project are defined. On the basis of this foundation, the detailed design is subsequently developed. This will include not only the technical features of the factory interior and exterior, the production equipment and the utility requirements, but also the deliverables in terms of cost, timescale and quality.

The project engineer's role during the construction phase, which is even more complex, is described in Chap. 20. Contractual issues dominate the early days, but the focus subsequently shifts to project planning, obtaining the necessary approvals and permits, site and construction issues, and, finally, completion of the project.

Appendix: Food factory design specifications listed in Bartholmai (1987)

Product(s) (origin of design)	Production rate	Total[a] and (equipment[b]) costs	Direct operating costs	Factory and (land[c]) areas	Production employees: total, (operators)
Fruit and vegetable products					
Apple processing plant: applesauce, canned, frozen, dehydrated, and fresh apple slices (USA)	5 t/h raw apples	\$2,923,260 (\$1,963,000)	Applesauce 24 ¢/can; canned slices 26.1 ¢/can; frozen slices \$389/t, dehydrated slices \$2,646/t	2,000 m^2 (5,000 m^2)	14 (7)
Community cannery: canned fruit and vegetables (USA)	200–1,000 containers (cans or glass jars) per day	\$204,000 (\$103,817)	Not given	150 m^2 (800 m^2)	Manager, two teachers (part-time retort operators plus clients)
Fruit purée plant: apricot, banana, mango, papaya, peaches, pear, plum, and strawberry (USA)	4 t/h fresh fruit yielding 3 t/h purée packaged in 20 l aseptic bags-in-box	\$1,100,000 (\$767,000)	\$197/t product	500 m^2 (2,000 m^2)	31 (24)
Multipurpose fruit-processing line: pasteurized fruit, fruit preserves, jams, and marmalade (Netherlands)	3 t/h of ingredients (fruit and sugar) yielding, e.g., 2.4 t/h of preserves or jams. Various packaging formats	Total cost not given (\$401,600)	\$169/t jam or preserve	100 m^2 (land area not given)	4 full time (3)
Orange juice concentrate plant: orange juice concentrate (62°Brix) and orange oil (Italy)	20 t/h oranges yielding 1.6 t/h concentrate packaged in 200 kg drums plus 85 kg/h oil	\$2,057,500 (\$1,016,500)	\$1,835/t product	2,000 m^2 (5,000 m^2)	16 (10)
Baby food line: fruit, vegetable, and meat products (Switzerland)	6 t/h raw materials yielding 5 t/h baby food packed in glass jars	\$200,000 (\$177,000)	\$120/t product (excluding cost of raw materials)	300 m^2 (land area not given)	2 (2)
Tomato paste plant: tomato paste, 32 % solids (USA)	15 t/h fresh tomatoes yielding 2.5 t/h paste packaged aseptically in 20 l cans or 200 l drums	\$1,837,000 (\$1,042,085)	\$1,700/t product	Factory/land areas not given	29 (20)
Frozen vegetable plant: okra, paprika, artichokes, spinach, cauliflower, broccoli, peas, green beans, etc. (Denmark)	4.4 t/h of field peas yielding 2 t/h frozen peas packaged in 25 kg bags	\$1,350,000 (\$803,820)	\$1,240/t product	3,000 m^2 (10,000 m^2)	50 (43)

Mushroom farm: fresh straw mushrooms packaged in bulk (UK)	80 t/year fresh mushrooms	\$116,500 (\$41,000)	\$1,950/t product (Malaysia)	6,000 m^2 (30,000 m^2)	10 (8)
Tofu plant: tofu packaged in 300 g cakes (Japan)	300 kg/h soy beans yielding 1,200 kg/h tofu	Total plant cost not stated (\$350,000)	Not stated	Not stated	10 (6)
Cornstarch plant: cornstarch, corn germ, gluten, and gluten feed. 70 % of sales to the food industry; 30 % for non-food use (Germany)	200 t/day clean corn yielding 302 t/day starch milk (37 % solids), 127 t/day cornstarch plus corn germ, gluten feed, and gluten meal	\$30,298,000 (\$13,680,000)	\$289/t product (corn starch)	2,400 m^2 (20,000 m^2)	53 (18)
Dairy products					
Mozzarella cheese plant: mozzarellas and pizza cheese (Italy)	40 kl/day milk yielding 5,000 kg/day pasta filata (120–150 g mozzarellas and 1–5 kg vacuum bags of pizza cheese)	\$841,600 (\$340,750)	\$980/t product	1,500 m^2 (10,000 m^2)	8 (4)
Blue cheese plant: mild blue, full-fat soft cheese (Germany)	95 kl/day raw milk (3 % fat) yielding 17 t/day blue cheese; 50, 600 and 1,200 g packages	\$4,093,000 (\$2,860,000)	\$369/t product	\$11,300 m^2 (\$30,000 m^2)	31 (22)
Dairy plant: various liquid milk products and whipping cream (Sweden)	50,000 t/year raw milk yielding 120 t/day whole milk, 40 t/day standardized milk, 2 t/day skim milk, 4 t/day whipping cream, 15 t/day cultured milk	\$13,530,000 (\$6,600,000)	\$185/t milk	7,000 m^2 (20,000 m^2)	115 (87)
Modular dairy plant: various liquid milk products and cream (Switzerland)	20 kl/day raw milk yielding 9.3 kl/day whole milk, 10 kl/day sour milk, and 0.7 kl/day cream packaged in ¼, ½ and 1 l cartons and cups	\$1,209,550 (\$675,200)	\$190/kl product	Factory area not given (1,500 m^2)	13 (9)
Powder milk plant: skim milk powder (Denmark)	18 t/h skim milk yielding 1.67 t/h skim milk powder packaged in 25 kg paper bags	\$4,000,000 (\$2,700,000)	\$1,213/t product	1,500 m^2 (land area not given)	10 (6)
Yoghurt plant: flavored yoghurt packaged in 150 g cups destined for the retail trade and institutional customers (Germany)	8 t/h raw milk and other ingredients (skim milk powder, sugar, cultures, fruits, additives) yielding 8 t/h yoghurt	\$4,827,600 (\$3,236,600)	\$510/t product	8,500 m^2 (20,000 m^2)	35 (28)

(continued)

Appendix: (continued)

Product(s) (origin of design)	Production rate	Total[a] and (equipment[b]) costs	Direct operating costs	Factory and (land[c]) areas	Production employees: total, (operators)
Ice cream plant: ice cream, various formats (Denmark)	2,000 l/h ice cream, including ice cream bars (with or without chocolate coating), cones, cups, family packs (½, 1 l), and tubs (2.5, 5, 10 l)	\$2,515,000 (\$1,330,000)	\$380/kl product	1,700 m^2 (5,000 m^2)	28 (17)
Cereals, baked products, and pasta					
Parboiled rice plant: parboiled paddy to supply an adjacent rice mill (Italy)	5 t/h clean paddy yielding 5 t/h parboiled paddy. The adjacent mill will produce 2.5–3.5 t/h parboiled rice	\$1,379,500 (\$888,000)	\$8.04/t product	600 m^2 (2,000 m^2)	16 (10)
Pan bread bakery: bread loaves (white, wholemeal, cracked wheat, milk, etc.), sliced or unsliced, sold to retail and wholesale markets (Italy)	1.5 t/h flour yielding 2.2 t/h pan bread packaged in 500 or 700 g plastic bags	\$2,803,000 (\$1,719,600)	\$355/t product	2,800 m^2 (10,000 m^2)	25 (18)
Arabic bread bakery: Arabic bread loaves (18 cm dia) packaged in PE bags for the retail trade (5 loaves/bag) (USA)	1,190 kg/h flour yielding 1,700 kg/h Arabic bread (14,400 loaves/h)	\$1,271,750 (\$659,150)	\$284/t product	1,000 m^2 (4,000 m^2)	27 (22)
Half-baked frozen baguette bakery: half-baked frozen baguettes for sale to supermarkets and the retail trade (Switzerland)	480 kg/h flour yielding 540 kg/h product packaged in 9 kg corrugated cardboard boxes	\$1,953,000 (\$1,188,850)	\$545/t product	1,056 m^2 (6,000 m^2)	15 (10)
Pasta plant: long-cut pasta (for spaghetti, vermicelli, etc.) and short-cut pasta (for macaroni, penne, etc.) (Italy)	663 kg/h wheat flour yielding 300 kg/h long-cut pasta and 350 kg/h short-cut pasta packaged in 250 and 500 g packs	\$2,353,000 (\$1,714,000)	\$474/t product	2,000 m^2 (10,000 m^2)	19 (11)
Precooked lasagna plant: precooked lasagna packaged in 10 kg cartons for institutional use (Italy)	630 kg/h durum semolina yielding 600 kg/h precooked lasagna	\$3,261,000 (\$2,211,800)	\$586/t product	1,150 m^2 (4,000 m^2)	19 (12)

Fermented products					
Baker's yeast plant: fresh baker's yeast (*Saccharomyces cerevisiae*) and active dry yeast for sale to bakeries and retail stores (Austria)	60 t/day molasses yielding 25 t/day fresh baker's yeast containing 30 % solids packaged in 500 g blocks and 6,670 kg/day active dry yeast packaged in 500 g, 1 kg bags	$26,550,000 ($9,776,000)	$1,224/t product	8,000 m^2 (40,000 m^2)	71 (59)
Vinegar plant: distilled white and wine vinegar for the retail trade and industrial users (Germany)	720 l/day alcohol (100 % basis) yielding 6,700 l/day vinegar (10 % acidity). Packaged in 500 ml bottles (5 % acidity) for the retail trade and in bulk (10–14 % acidity) for industrial users	$750,000 ($498,700)	$212.9/kl wine vinegar (10 %)	375 m^2 (2,000 m^2)	8 (3)
Snacks					
Tortilla chip plant: tortilla chips packaged in 500 g flexible bags for the retail trade (USA)	450 kg/h of raw corn yielding 500 kg/h tortilla chips	$1,688,000 ($1,250,000)	$820/t product	950 m^2 (4,000 m^2)	24 (10)
Corn snacks plank: extruded baked corn snacks of different shapes packaged in 300 g flexible bags for the retail trade (USA)	160 kg/h of corn meal yielding 250 kg/h corn snacks	$310,000 ($122,425)	$430/t product	500 m^2 (2,000 m^2)	7 (3)
Seafood, meat, and egg products					
Catfish processing plant: frozen, whole dressed fish, fish fillets, and fish nuggets packaged in 5 and 10 kg boxes for institutional and wholesale markets (USA)	3.2 t/h live fish yielding 1,120 kg/h dressed fish, 485 kg/h shank fillets and 65 kg/h fish nuggets	$2, 400,000 ($1,011,803)	$3,593/t product	1,200 m^2 (10,000 m^2)	31 (27)
Shrimp processing plant: raw, peeled, deveined, and graded frozen shrimp packaged in 2 kg cartons for institutional and wholesale markets (USA)	500 kg/h raw shell-on shrimp yielding 250 kg/h frozen product	$431,000 ($191,700)	$2,205/t product	600 m^2 (2,000 m^2)	14 (10)
Surimi plant: three grades of surimi (10 kg frozen blocks) plus premium pollock fillets for	15 t/h raw pollock yielding 3.33 t/h surimi (three grades),	$10,000,000 ($5,899,600)	$230/t pollock	11,500 m^2 (20,000 m^2)	142 (114)

(continued)

Appendix: (continued)

Product(s) (origin of design)	Production rate	Total[a] and (equipment[b]) costs	Direct operating costs	Factory and (land[c]) areas	Production employees: total, (operators)
foodservice or retail markets, pollock meal, and oil (USA)	750 kg/h fillets, 1.4 t/h meal, and 250 kg/h oil				
Cattle slaughterhouse: dressed beef carcasses packaged in stockinette and polyethylene (Uruguay)	80 head of cattle/h yielding 16 t/h dressed beef carcasses	\$3,660,000 (\$930,000)	\$1,047/t product	5,200 m^2 (30,000 m^2)	180 (169)
Co-extruded sausage plant: frankfurter sausages packaged in sterilized cans or pasteurized clear plastic for the retail trade (Netherlands)	1 t/h of sausages from sausage meat and collagen fiber paste	\$2,000,000 (\$1,000,000)	\$220/t product	1,000 m^2 (5,000 m^2)	7 (3)
Protein recovery plant: meat meal, tallow, and blood meal from animal by-products. Sold as high-protein feed supplements (USA)	12 t/h of fresh animal by-products from a 1,500 head/day cattle slaughterhouse yielding 6 t/h of product	\$2,671,000 (\$1,900,000)	\$82/t product (excluding cost of raw materials)	1,000 m^2 (3,000 m^2)	11 (4)
Quenelle plant: quenelles (dumplings formulated from cereals, meat, dairy products, and fruit and vegetables) (France)	600 kg/h of quenelles vacuum packaged as 20–180 g bars or other shapes	\$985,000 (\$476,000)	\$730 t/product	350 m^2 (2,000 m^2)	9 (5)
Dried whole egg plant: whole egg powder packaged in PE-lined boxes (net weight 25 kg) (USA)	360,000 shell eggs per day yielding 238 kg/h whole egg powder	\$2,287,200 (\$1,302,500)	\$3,859/t product	1,200 m^2 (3,000 m^2)	24 (18)
Fats and oils					
Soybean oil extraction plant: crude oil, high protein meal, crude lecithin, and toasted hulls from soybean. The crude oil is sold to refiners, the meal and hulls are supplied to feed mills, and lecithin is used as an emulsifier (Germany)	1,000 t/day soybeans yielding 169 t/day crude soybean oil, 800 t/day meal (44 % protein), 7 t/day crude lecithin and 80 t/day toasted, milled hulls	\$24,900,000 (\$5,929,000)	\$258.5/t soybeans	2,500 m^2 (40,000 m^2)	61 (34)

Vegetable oil refinery: cooking oil packaged in 20-l drums and 500, 1,000-ml bottles. Sold to institutional and retail markets (USA)	2 t/h crude vegetable oil (peanut, soybean, sunflower, corn, cottonseed, etc.) yielding 1.8 t/h cooking oil	\$2,359,000 (\$1,320,000)	\$735.3/t product	1,000 m^2 (10,000 m^2)	37 (25)
Beverages					
Seawater desalination plant: potable water by multistage flash distillation of seawater (Austria)	3,100 t/h sea water yielding 417 t/h potable water	\$18,433,000 (\$8,043,000)	\$2.86/m^3 potable water	110 m^2 (3,000 m^2)	21 (20)
Fruit juices plant: reconstituted fruit juice packaged in 25 cl pouches from fruit juice concentrate or fruit purées. Sold to retail market (France)	2 kl/h reconstituted fruit juice (e.g., orange) containing 14 % solids	\$809,000 (\$497,000)	\$0.104/pouch	724 m^2 (5,000 m^2)	10 (6)
Soymilk plant: soymilk packaged in 200 ml aseptic packs and sold to the retail trade (Japan)	150 kg/h soybeans (12 % moisture) yielding 1,000 l/h soymilk	Total plant cost not given (\$910,000 excluding aseptic sterilizer)	Not given	Not given	6 (2)

[a] Excluding cost of land

[b] FOB point of manufacture

[c] Nonurban site

References

Baker, C.G.J. (1997) (ed.) “Industrial drying of foods”, Blackie Academic & Professional, London, 309 pp.

Barbosa-Cánovas, G.V. and Zhang, Q.H. (2001) “Pulsed electric fields in food processing”, Technomic, Chicago, 268 pp.

Barbosa-Cánovas, G.V., Tapia, M.S. and Pilar Cano, M. (2005) “Novel food processing technologies”, CRC Press, Boca Raton, FL, 692 pp.

Bartholmai, A. (1987) (ed.) “Food factories. Processes, equipment, costs”, VCH Verlagsgesellschaft, Weinheim, Germany, 289 pp.

Brennan, J.G. (2006) “Food processing handbook”, Wiley-VCH, Weinheim, Germany, 582 pp.

Doona, C.J. and Feeherry, F.E. (2007) (eds) “High pressure processing of foods”, Wiley-Blackwell, Hoboken, NJ, 272 pp.

Fellows, P.J. (2009) “Food processing technology: Principles and practice”, 3rd edit., Taylor & Francis, Boca Raton, FL, 913 pp.

Holah, J. and Lelieveld, H.L.M. (2011) “Hygienic design of food factories”, Woodhead, Cambridge, 784 pp.

Hui, Y.H., Ghazala, S., Graham, K.D., Murrell, K.D. and Nip, W-K. (2003) “Handbook of vegetable preservation and processing”, Marcel Dekker, New York, 752 pp.

López-Gómez, A. and Barbosa-Cánovas, G.V. (2005) “Food plant design”, CRC Press, Press, Boca Raton, FL, 416 pp.

Larousse, J. and Brown, B.E. (1997) (eds) “Food canning technology”, Wiley-VCH, Weinheim, Germany, 720 pp.

Olver, L. “The food timeline”, http://www.foodtimeline.org.

Ramaswamy, H.S. and Marcotte, M. (2006) “Food processing: Principles and applications”, CRC Press, Boca Raton, FL, 420 pp.

Ranken, M.D., Kill, R.C. and Baker, C.G.J. (1997) (eds) “Food industries manual”, Blackie Academic & Professional, London, 650 pp.

Saravacos, G.D. and Kostaropoulis, A.E. (2002) “Handbook of food processing equipment”, Springer, NewYork, 698 pp.

Singh, R.P. and Heldman, D.R. (2009) “Introduction to food engineering”, Academic Press, San Diego, CA, 841 pp.

Smith, J.S. and Hui, Y.H. (2004) (eds) “Food processing: Principles and applications”, Wiley-Blackwell, Hoboken, NJ, 511 pp.

Sun, D-W. (2005) “Emerging technologies for food processing”, Academic Press, San Diego, CA, 771 pp.

Walstra, P. Wouters, J.T.M. and Geuts, T.J. (2006) “Dairy science and technology”, CRC Press, Boca Raton, FL, 692 pp.

Part I
Process Considerations

Chapter 2
Process Specification

D.L. Pyle[†]

2.1 Introduction

2.1.1 Evolution of the Design

Food processing is concerned with transforming raw materials into edible, safe, and nutritious products to meet a human and/or market need. The design problem is to establish and specify the mix of operations (i.e., machines) and material requirements, which, with appropriate scheduling, can produce defined quantities of the required products with assured quality and form. Very few factories produce only one product or an unchanged product mix day in, day out: different raw materials are available at different times of the year; the market demands variety, and few products are made on a sufficient scale to merit a dedicated line. Thus, it is not uncommon to find many recipe and/or product changes on a production line. This may involve using the same equipment (after a cleaning cycle); it may involve changes in the food processing operations or their sequence. The "recipe" is thus the specification of the materials and the operating sequence. The products must meet defined quality measures, implying defined levels of consistency, hygiene, and control in the production process. The processes should therefore be flexible and robust. In other words, they must be able to cope with variations in raw materials and other disturbances. The production system should also be efficient in the use of materials, energy and other services; rapid and efficient product changeover will be important; materials and other aspects of processing history should be traceable. Ideally the factories will be flexible enough to cope with new products. Above all, the process must meet defined economic objectives within the resource constraints on people, equipment and services.

Many food operations are inherently risky and it is therefore very important that, at defined intervals, the process equipment can be thoroughly and reliably cleaned. Hence, CIP must be included as part of the design remit from the outset. Also, most processing lines involve a mix of continuous and batch or semi-batch operations. This poses special problems for process operability, scheduling, and control.

The design of a production facility evolves through a series of iterations (Fig. 2.1), beginning with a definition of the products and their recipes. This leads to a simplified flowsheet. From this, preliminary estimates of the materials, energy and service requirements can be produced. The flowsheet can also

---

[†] deceased

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_2,

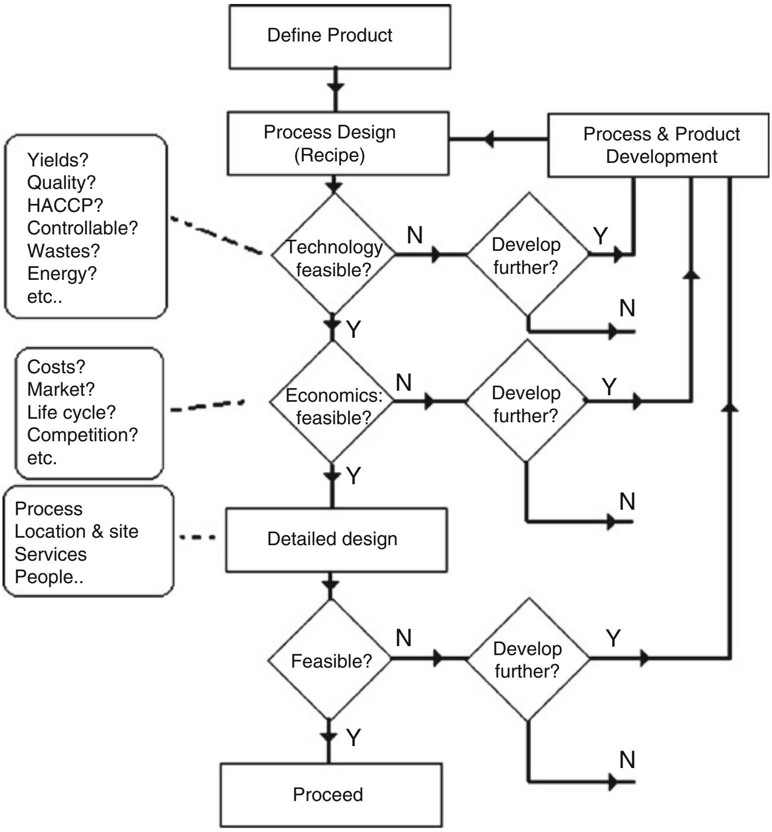


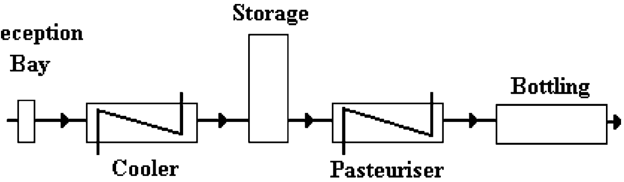
Fig. 2.1 The design cycle

be used at an early stage for the preliminary study of important aspects such as microbial (and other) hazards and their control, process control and operational feasibility. These form the basis for a preliminary economic analysis. From this, the flowsheet is further refined and more detailed analysis of all these aspects can be pursued. The design specification thus develops through a hierarchy of levels. Here we focus mainly on the first stages of design, i.e., defining a process to a stage at which specification of the details of the process and its operation can proceed.

2.1.2 Flowsheeting

Usually the specification of an outline flowsheet is relatively straight forward, in that there are relatively few really novel products. Most “new” food products are developments from existing products and processes, involving either new ingredients and operating methods or sometimes new technology at one stage of the sequence. Of course, at a more detailed level, the differences between one company’s process and another’s may be considerable, even if this is not immediately obvious from the outline flowsheet. A key stage in developing successful new products is to solve the scaling problem, i.e., to find and use the rules which ensure satisfactory development from the kitchen or product development laboratory to the industrial scale, producing hundreds of kilograms or tonnes of products. Although many of the basic rules of scale up are understood, the complexity (and rapid product cycle) associated with food processing means that it is often unsafe to jump straight from laboratory to production scale. In other words, be careful before you drop the pilot-scale trials.

Fig. 2.2 Milk bottling line



Two examples of flowsheets are shown here. Figure 2.2 is a simplified, outline flowsheet of a line to produce and bottle pasteurized milk. The milk is received from a tanker where it is held in cool storage until the pasteurizing and bottling line becomes available or the production schedule (of which, more later) demands it. Then the milk is pasteurized continuously en route to the bottling plant. Note that this flowsheet is extremely basic: it does not show any of the necessary CIP features, waste streams, services, or alternative feed streams. At this level, the flowsheet is simply a representation of the processing sequence; no further implications (e.g., that there is only one storage tank, that milk from only one source is to be used, or that the pasteurizer is dedicated to this line, etc.) should be drawn. On the other hand, together with the product specification, it does embody sufficient features of the process to enable *preliminary* estimation of the material and energy requirements (i.e., how many bottles, how much steam and cooling water or refrigerant are required per tanker load) to be made.

The second example is a more detailed flowsheet of a (hypothetical) potato-frying process. Figure 2.3 is a block diagram listing the sequence of operations, while Fig. 2.4 shows the main process vessels, lines, and service supplies, but not the detailed instrumentation. This flowsheet is sufficiently detailed to permit a reasonably accurate assessment of the material and energy requirements, and equipment sizing. Also the flowsheet can be used to form the basis for HACCP (*H*azard *A*nalysis and *C*ritical *C*ontrol *P*oints) and related quality and process control studies. In the case of the frying process, many of the process steps shown in Fig. 2.4 can be identified as critical control points (CCPs). However, the principal concern is for the post-frying steps, since snacks are susceptible to post-processing contamination, and none of the processing steps after the fryer can positively reduce or eliminate the hazards. This has clear implications for *process* control since the HACCP analysis is based on a presumption that the various stages are operated in the way the design team intends.

Traditionally, HACCP analyses have been monitored and recorded manually, despite the fact that several good computer-driven HACCP analysis programs are available. Table 2.1 lists a number of Web sites that advertize such software. This list is not intended to be comprehensive and the reader is advised to undertake a detailed and up-to-date search to satisfy his requirements. In 2005, the International Organization for Standards published the ISO 22000 Food Safety Management Systems Standard, which supersedes the HACCP principles promulgated by the Codex Alimentarius Commission in 1993. The principal differences between this Standard, which was designed for easy incorporation into the ISO 9001 quality management system, and HACCP have been described by Blanc (2006).

Today we are in a position where all the process monitoring—including all the HACCP-driven, etc., actions—can be monitored and recorded electronically. This must be the way forward in developing efficient, integrated, and traceable systems.

2.2 Batch Processes: Scheduling and Its Implications

As already noted, batch and semi-batch operations are common in the food industry. This is because it makes a wide range of products on demand, often requiring relatively short processing runs, and because regular cleaning cycles are needed to maintain hygienic conditions. Equipment is shared between different products; there are frequent start-ups and shutdowns. Decisions have to be made

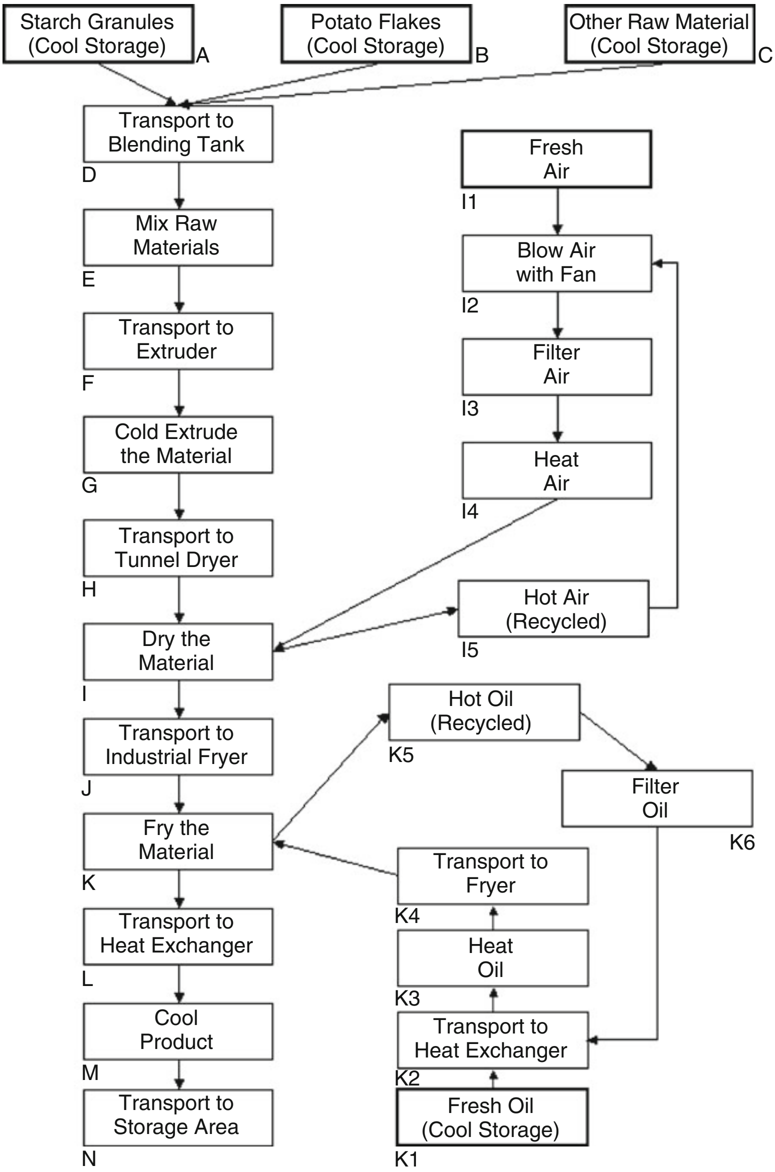


Fig. 2.3 Potato frying process

constantly as to which product to make, which tanks and processing equipment are to be used, and so on. The combination of many different but similar products and their perishability implies that time spent in the warehouse and distribution networks should be minimized; this intensifies the pressure on the production system.

It is important that these features are fully recognized at the design stage and here we concentrate on one or two simple examples to illustrate the methods and issues involved. The easiest way of visualizing a batch sequence is by means of a Gantt chart. In this diagram, the usage (including filling and emptying) of all the principal items of equipment is plotted versus time. In a multiproduct plant, different colors can be used to show their processing history.

Consider first a plant where a single product is made in a sequence of repeated batches using the same equipment, i.e., on a committed production line. For simplicity, the times to fill, empty, and

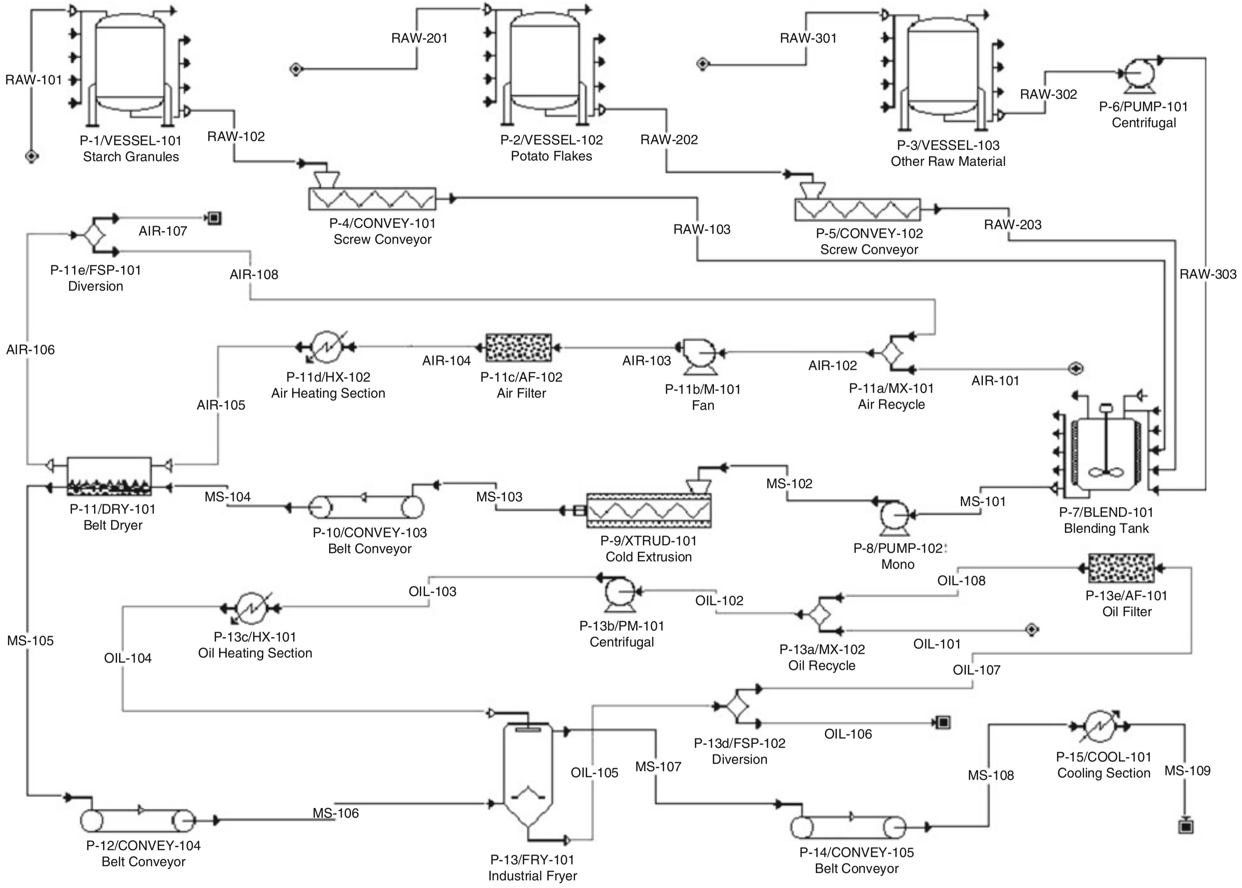


Fig. 2.4 Flowsheet of potato-frying process

Table 2.1 Selection of Web sites that advertize HACCP software

Software	Organization	URL
Food Safety Management System (FSMS)	EtQ, New York, NY, USA	http://www.etq.com/haccp
HACCPweb	One World Learning Ltd, Cork, Eire	http://www.haccpweb.com
HaccpHelp	HACCPHelp Software, Inc., Caledon, ON, Canada	http://haccphelp.com/haccphelp_software.htm
doHACCP	Norback, Ley & Associates, Middleton, WI, USA	http://www.norbackley.com
HACCP Control Point	Vertical Software International, London, ON, Canada	http://www.haccp.ca
HACCP Software	HACCP Builder, St. Paul, MN, USA	http://www.haccpbuilder.com
HACCP Now	HACCP Now, UK	http://www.haccpnow.co.uk
HACCP Software	HACCP Software, Dublin, Eire	http://www.Haccpsoftware.com

Last accessed 14 September 2011

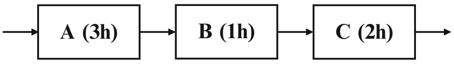


Fig. 2.5 Flowsheet of hypothetical 3-stage batch process

clean between operations are neglected. The flowsheet (Fig. 2.5) shows a hypothetical process with three batch stages A, B, and C lasting 3, 1, and 2 h respectively. Figure 2.6a shows the Gantt chart for nonoverlapping operation. The chart shows that none of the equipment is used continuously; batches (indicated by "*P*") are produced every 6 h. Figure 2.6b shows how this plant is used with overlapping operation. Now Stage A is fully occupied and batches are produced every 3 h. Since Stage A is used continuously the only way of further speeding up the process would be to remove the bottleneck by duplicating this piece of equipment (which of course raises a cost issue). The result is shown in Fig. 2.6c. This can be speeded up further by duplicating Stage C (Fig. 2.6d). The minimum batch time and maximum equipment utilization could be achieved by using three Stage A units, one Stage B unit and two Stage C units.

The "rules" governing the batch cycle times are relatively easily seen from this example. For nonoverlapping operations, the batch cycle time is the sum of the individual stage batch times (i.e., $3 + 1 + 2 = 6$ h). For overlapping operations, with no duplicate equipment, the batch cycle time is the time needed to complete the slowest individual stage (i.e., here 3 h). With overlapping operation the (average) batch cycle time is the maximum value of the ratio of the batch time to the number of duplicates as calculated for each stage. Thus, referring to Fig. 2.6c—with Stage A duplicated—the batch cycle time $= \max\{3/2, 1, 2\} = 2$ h. When both Stages A and C are duplicated, the batch cycle time is reduced to $\max\{3/2, 1, 2/2\} = 1.5$ h, as may be confirmed from Fig. 2.6d, which shows two batches every 3 h. Note that the cycle time could be reduced to 1 h by using a third Stage A.

If the total daily production of this particular product is fixed, then the strategies outlined above have implications for the batch scale and therefore the size of the equipment. This is illustrated in Table 2.2 in which the four strategies are compared, assuming 24-h production per day, and a daily production of 1,000 kg product. The economic and operating implications of these choices must be explored at an early stage of the design process.

Consider now the typical situation where the factory manufactures more than one product. For similar products this is likely to imply the use of the same stages in the same sequence. For dissimilar products it is likely that different stages and/or sequences will be used. For these situations the cycle times can usually only be obtained by computation. To illustrate the problem, we use a simple

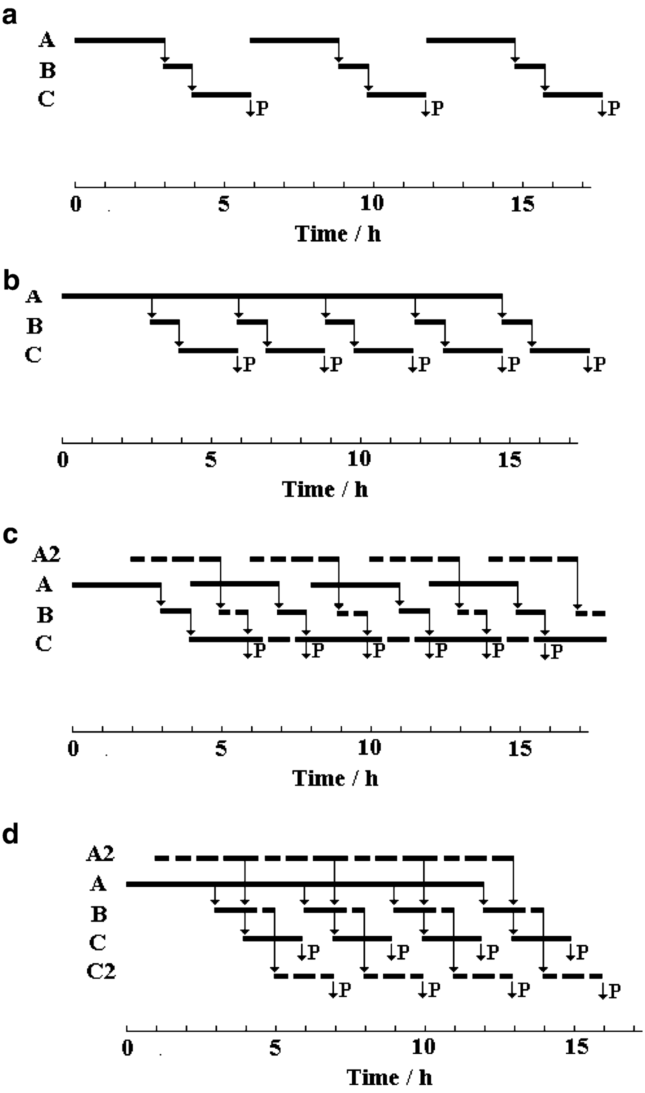


Fig. 2.6 3-Stage batch process: (**a**) Gantt chart—nonoverlapping operation, (**b**) Gantt chart—overlapping operation, (**c**) Gantt chart—overlapping operation, Stage A duplicated, (**d**) Gantt chart—overlapping operation, Stages A and C duplicated

Table 2.2 Effect of schedule on batch equipment size

Strategy	Batch cycle time (h)	No. of batches/24 h	Batch size (kg)
Nonoverlapping (Fig. 2.6a)	6	4	250
Overlapping (Fig. 2.6b)	3	8	125
Duplicate stage A (Fig. 2.6c)	2	12	83
Duplicate stages A and C (Fig. 2.6d)	1.5	16	62.5

three-stage process manufacturing two products X and Y, using the same equipment but with different processing times, as summarized in Table 2.3.

It is immediately obvious that the choice has to be made between a single-product campaign (i.e., XXX... YYY...) or a multiproduct campaign (e.g., XYXY...) as shown in Fig. 2.7a, b, in which the clean up time between X and Y is neglected. Arbitrarily it is assumed that three batches of each product are to be made. In this example, the mixed-product campaign is less time-efficient than

Table 2.3 A multiproduct process

	Batch times (h)		
Product	Stage A	Stage B	Stage C
X	3	2	1
Y	1	1	1

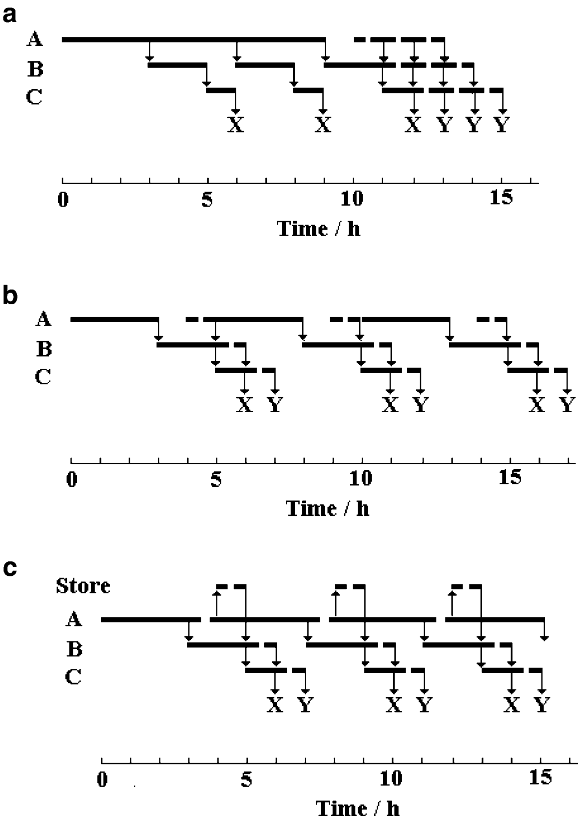


Fig. 2.7 Manufacture of more than one product: (**a**) Gantt chart for single product campaign, (**b**) Gantt chart for multiproduct campaign, (**c**) Gantt chart for multiproduct campaign with intermediate storage

the single-product campaign. (The total production time for the single product campaign is 15 h; that for the multiproduct campaign is 17 h.) The situation is less favorable still if there is an additional clean up time between products *X* and *Y*. In other situations, however, the mixed-product campaign may be more resource efficient.

Suppose, however, that the mixed-product campaign (Fig. 2.7b) is preferred. What can be done to improve its efficiency? We have already seen the potential advantages of duplicating equipment that acts as a bottleneck. In fact there is no bottleneck in the scheme shown in Fig. 2.7b. At some stage in the production cycle *all* three stages are idle. This suggests that some intermediate storage should be considered (but in food processing, the opportunities will be constrained). For example, Fig. 2.7c shows the effect of introducing an intermediate storage tank for product Y after stage A. This improves the time efficiency for the multiproduct campaign to a level comparable with that of the single product campaign.

Intermediate storage can also be useful with single-product campaigns, since it can help to decouple the stages so that each can operate with its own cycle time and batch size. This is illustrated in Fig. 2.8. Here the flowsheet corresponding to Fig. 2.6b has been modified by introducing two intermediate storage vessels between Stages A and B and B and C. The storage tanks are sized such

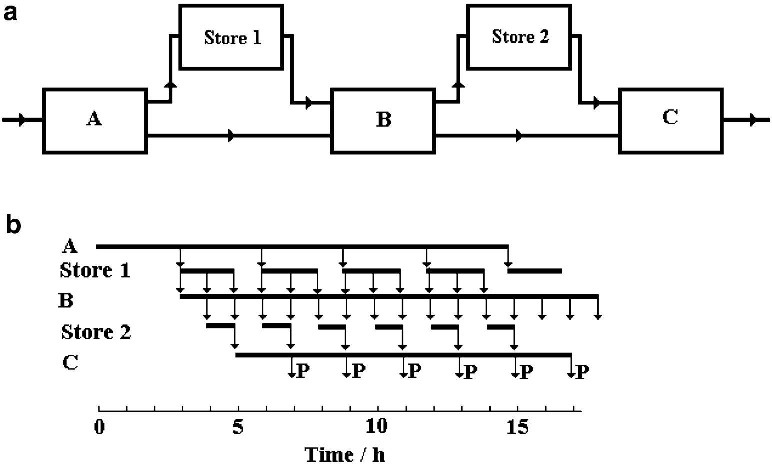


Fig. 2.8 3-Stage process with storage: (a) Flowsheet, (b) Gantt chart

that the first holds two-thirds of the batch discharged from Stage A, and the second holds one "batch" from Stage B. The Gantt chart shows that whilst there is no effect on the overall cycle time, idle time on Stages B and C has been eliminated. These stages can now be smaller than those specified in the original design. The economic and operating consequences should therefore be explored before the plant design is confirmed.

Today, computer-based methods for analyzing production sequencing are available and complex systems can be readily analyzed, although real-time optimization is still a target for the future.

2.3 Estimating Material and Energy Requirements

The outline flowsheet, the production targets and the operating conditions, such as the temperature of the cool milk fed to the storage tank or the temperature–time profile required for batch pasteurization, form the basis for preliminary estimation of the flows of materials and energy through the process. These estimates start from the assumption that mass and energy are conserved—i.e., they are neither created nor destroyed. The "form" they take may change profoundly during processing: raw materials are transformed into finished products; the energy used in mixing flour, water and fat helps to convert the mixture into dough with very different physical and biochemical characteristics from the raw materials, and so on. Some of the general principles underpinning material and energy balances are outlined first. The application of material balances and energy balances is then described.

2.3.1 Mass Balancing

2.3.1.1 Law of Conservation of Mass

Ultimately, it is the chemical elements that are conserved. Thus, whether or not reactions occur, one can, in principle, always establish an elemental balance. However, in food processing this is hardly ever convenient or possible. But the fact that the elements are conserved means that mass is also conserved; we shall develop this in more detail below. Moreover, in processes involving only liquid streams, volume conservation can often be assumed as a reasonably adequate first approximation.

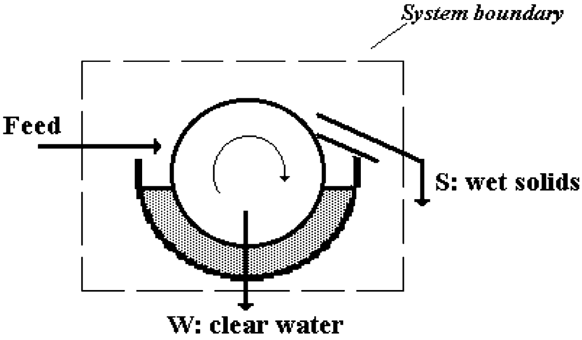


Fig. 2.9 Rotary filter

2.3.1.2 Closed and Open Systems

If a mass or energy balance is to be set up, the statement that mass and energy are conserved is meaningless unless the system and its boundaries are defined. A system can be part of an operation, a whole operation (such as a mixer), a production line or a whole factory. Systems may be defined as Closed or Open. A *closed system* is one in which there is no material transfer across the defined boundaries—for example, a sealed can of peas being sterilized in a retort. In contrast, in an *open system*, material may be transferred in and out across the boundaries. A continuous fermenter or a food extruder are examples of open systems.

In the case of batch processes, the definition of the system will also involve time (e.g., the start and end of a process cycle).

Example 1. 100 kg of a waste stream containing 10 wt% suspended solids is separated in a vacuum filter to produce clear water and slightly wet solids containing 2 wt% moisture. How much of each stream is produced?

The total amount of feed to the process, 100 kg, is taken as the basis of the calculation. The choice of basis is important, and should always be stated. The boundaries of the system—the filter itself—are shown as a broken line in Fig. 2.9. This is an open system; the input and output streams (all of which must be accounted for in the balance) cut the system boundary.

Assuming that no material accumulates in the filter, conservation of mass implies that the total quantities of water and solids respectively into and out of the system remain constant. Note that the feed contains 90 kg water and 10 kg dry solids. The wet solids product stream contains 2 % water and 98 % dry solids. Then if S and W are the total masses of the wet solids and clarified water, balances on the total flows, dry solids and water respectively are:

$$100 = W + S. \tag{2.1}$$

$$10 = 0.98S. \tag{2.2}$$

$$90 = W + 0.02\mathrm{S}. \tag{2.3}$$

From (2.2), $S = 10.20$ kg, and from (2.1), $W = 89.80$ kg.

Note that although there are three equations and only two unknowns, there is no mathematical problem here, since only two (any two) of the equations are independent. Given balances on the two components (water and dry solids) the overall balance immediately follows. This can be checked by substituting the values for S and W into (2.3). Alternatively, the problem could be solved by solving either (2.2) and (2.3) or (2.1) and (2.3). Choose the simplest!

This method can easily be extended to processes with more unchanging components. The solution, by repeated substitution, is normally straightforward when the number of equations is small.

Table 2.4 Mass balance for Example 1

Component	Stream F/kg	Stream S/kg	Stream W/kg
Water	90	0.2041	89.7959
Solids	10	10	0
Total	100	10.2041	89.7959

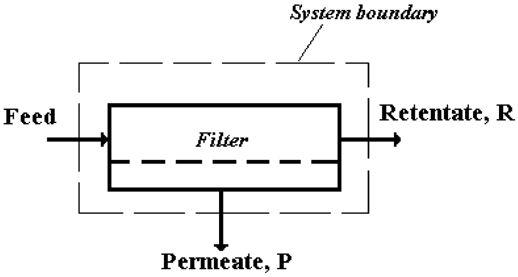


Fig. 2.10 Cross-flow membrane filtration

The results can be represented in many ways. It is often convenient to present the data in tabular (e.g., spreadsheet) form, making checking straightforward, as shown in Table 2.4.

In this example, since there is no reaction between the components, the entries in each of the boxes in the second column (the inputs to the system) must balance the sum of the entries on the same row in the third and fourth columns (i.e., the sum of the output streams).

This simple example also provides insights for developing some important concepts and rules. The first concept is that of the basis for a calculation.

2.3.1.3 The Choice of Basis

Few real-world problems have such an obvious basis for the calculation as the example above. A more typical process-engineering design will start with a brief to produce a defined amount of product. For example, a company may want to produce 10,000 pots of yogurt. Even with a well-defined flowsheet, back-calculation (i.e., from the product) is extremely inconvenient. Calculation is normally easiest when the "flows" of information and mass are in the same direction. Thus, it is far more convenient to carry out the calculation on the basis of, say, 100 kg of milk (i.e., an input to the process), and then, finally, to adjust the numbers throughout by the appropriate ratio.

Two useful principles apply to the choice of basis:

- Choose a basis which is convenient for subsequent calculation and checking.
- Don't change the basis during the calculation.

Example 2. A cross-flow membrane (Fig. 2.10) is used to concentrate an aqueous solution containing 5 wt% whey protein. The retentate (product) stream R is to contain 30 % protein; the separation is not perfect and the permeate P will contain 2 wt% protein. It is desired to produce 80 kg of protein per day in the retentate. Calculate the flows and compositions of all three streams.

Basis: Whilst it would be possible to choose 80 kg of protein, i.e., 80/0.3 or 266.67 kg of retentate, as basis, it is simpler to base the calculation on the feed. So we take the basis as 100 kg feed solution.

As before, we set up an overall balance and balances on the components—protein and water—remembering that only two of these equations are independent:

$$\text{Overall}: \quad 100 = R + P. \tag{2.4}$$

$$\text{Protein}: \quad 5 = 0.3R + 0.02P. \tag{2.5}$$

$$\text{Water}: \quad 95 = 0.7R + 0.98P \tag{2.6}$$

Solving any two of (2.4)–(2.6) gives:

$$P = 89.29\,\text{kg}.$$

$$R = 10.71\,\text{kg}.$$

Since the calculated retentate is not the design value (266.67 kg), all mass flows must be multiplied by 266.67/10.71, to give:

$$\text{Feed} = 2,489.0\,\text{kg}.$$

$$\text{Permeate} = 2,222.3\,\text{kg}.$$

$$\text{Retentate} = 266.7\,\text{kg}.$$

A complete check on both components is easily constructed, as in the previous example.

2.3.1.4 Losses

A key assumption in the above examples was that no material was lost during processing. In the real world, material is lost during cleaning, from spills, etc. The assumption of zero losses is a good starting point for a preliminary analysis, however. Historical data can be used to refine the calculations where necessary. Most important, calculations based on an assumption of "ideal" behavior provide an important reference point for analyzing plant performance in practice and for calculating the losses and wastage: the benefits of benchmarking for process efficiency should not be underestimated.

2.3.1.5 The Concept of Steady State

The examples above could refer either to batch or continuous operation. If the process is carried out continuously, the assumption that there is no change in the material inventory within the system implies that the system is steady—i.e., that it does not change with time.

For a steady non-reacting system, a balance on every component or the sum of the components (i.e., the total inputs and outputs) is:

$$\text{Mass in} = \text{Mass out}. \tag{2.7}$$

The balance can also be formulated in terms of rates of flow (e.g., expressed in kg/s) and, again, for every component and the total:

$$\text{Rate of mass flow in} = \text{Rate of mass flow out}. \tag{2.8}$$

For a reacting system, whilst balances on individual components will not be so simple (unless they are inert), the *overall* material balance must obey these equations.

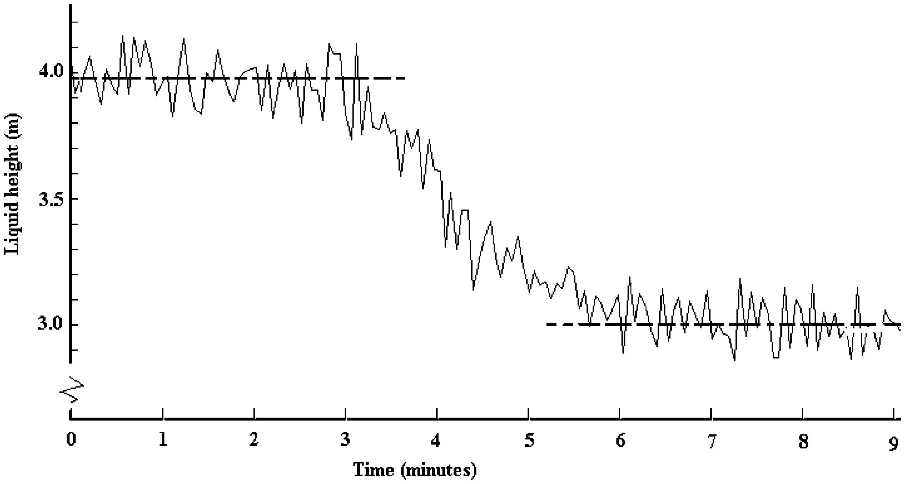


Fig. 2.11 Liquid level in process vessel

In practice, flowrates and compositions are never precisely constant, even though over a longer period the fluctuations average out. Instantaneously, then, the simple steady-state balance may not hold, as the system inventory or holdup changes to accommodate the fluctuations. Checking the mass balance from operating data on a process is never trivial. In a continuous process it is important to look at the time record of inputs and outputs. This is illustrated in Fig. 2.11, which shows the variations in liquid level in a continuously operating vessel. During the period shown, the system is moving from one steady state to another. In this example the measurements are "corrupted" (as in the real world) by noise. Figure 2.11 has three regions: over the first 3 min, the system fluctuates around a steady state, with an average liquid level just below 4 m. At any instant the system is not strictly steady, but over a period of a few minutes the system can be assumed, on average, to be steady. Between approximately 3 and 6 min, the plant is adjusting to a new set of conditions and is unsteady whether the timescale is of order seconds or minutes. After around 6 min, the level fluctuates around a new steady state value of 3 m. It is important, therefore, to be clear about the time scale over which the plant is analyzed and to differentiate between steady and unsteady operation.

If the system is such that changes in mass holdup are impossible (for example, with a constant-volume liquid mixer) then, even if one or more of the inputs changes with time, the system can be treated as if it were in steady state since the instantaneous flowrates in and out must balance. The simplest example is the flow of an incompressible fluid through a constant volume tank.

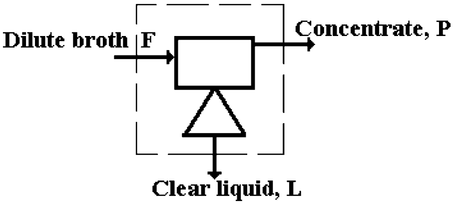
2.3.1.6 Batch Processes

Batch processes, such as a batch retort or a dough mixer, are, by definition, ones in which something changes with time—i.e., they are unsteady. However, in terms of overall process calculations, it can often be safely assumed that there is no net accumulation or loss within the system, provided the start and end of the batch cycle are properly specified.

2.3.1.7 Unsteady Systems

An unsteady system is one in which conditions within the system change with time. This might be a storage silo, a batch process, a warehouse, or, as in Fig. 2.11, during a change of operating conditions

Fig. 2.12 Centrifuge



in a continuous process. In this general case, the overall balance must account for the possibility of accumulation (or depletion). Taking as basis a fixed period of time or a defined quantity of a feed stream, the balance on any component, or their sum is, for a non-reacting system:

$$\text{Quantity accumulated} = \text{Quantity in} - \text{Quantity out} \tag{2.9}$$

or, instantaneously:

$$\text{Rate of accumulation} = \text{Rate of flow in} - \text{Rate of flow out.} \tag{2.10}$$

Example 3. A continuous cornflake production process includes a surge tank between the dryer and the toaster. The process is designed to operate steadily at a flowrate of 10 t/h. However, the feed flowrate may change by up to 2 t/h for periods of up to 30 min. What size of surge tank is necessary if the flowrate to the toaster is not to be interrupted during the operation?

Basis: Thirty minutes operation.

During a surge in inlet flow, the system is unsteady and the maximum total change in inventory during half an hour of increased or decreased inlet flow is ±1 t. Thus, the surge tank would need to have a capacity of at least 2 t to cope with the foreseen surges, assuming that under normal steady operation the tank was run half full. This assumes that the probability of two successive surges in the same direction is very small. Is the answer realistic?

2.3.1.8 Inert Materials

Many processes involve inerts—i.e., components, which pass through the process unchanged. For example, atmospheric nitrogen can be treated as an inert in aerobic fermentations.

Sometimes an inert component, which enters in one stream and leaves in another, can be a convenient "hanger" on which to base—and simplify—a calculation. This is known as a "tie" substance. The solids in Example 1 are, in effect, a tie substance.

Example 4. A product stream F from a baker's yeast fermenter contains 5 wt% yeast cells as suspended solids. The plant produces 100 kg of dry yeast/day. The broth is concentrated in a continuous centrifuge into a stream P containing 15 wt% suspended solids and clear liquid L, some or all of which could potentially be recycled. What is the maximum amount of clear liquid, which could be recycled?

Basis: 100 kg/day dry yeast (i.e., 1 day's production).

The process is illustrated in Fig. 2.12. In this case the 100 kg of yeast can be treated as a tie substance. Assume that the broth comprises cells and (clear) liquid. An overall balance (in kg/day) gives:

$$F = P + L$$

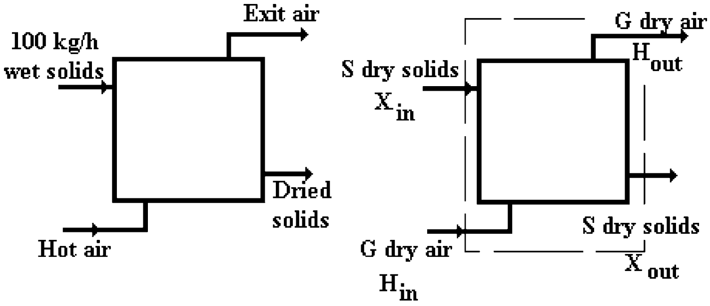


Fig. 2.13 Continuous dryer

and a balance on the tie substance gives

$$100 = 0.05F = 0.15P,$$

whence:

$$F = 2{,}000\,\text{kg}.$$

$$P = 666.7\,\text{kg}$$

$$L = 1{,}333.3\,\text{kg}.$$

2.3.1.9 Wet and Dry Basis

The concept of a tie substance is also useful with processes such as humidification and air drying. The mass concentration of water vapor in air is usually defined in terms of humidity, i.e., the mass of water vapor per unit mass of dry air (*not* the mass of water vapor per kg of moist air). In a similar way, the moisture content of a wet solid can be defined on a *wet basis* (i.e., X_w kg water/kg wet material) or on a *dry basis* (i.e., X_d kg water/kg dry solids). It is easily shown that:

$$X_w = X_d/(1 + X_d) \tag{2.11}$$

and

$$X_d = X_w/(1 - X_w). \tag{2.12}$$

Suppose we have F kg moist solids with moisture content X_w (wet basis). The quantity of dry solids is $F(1 - X_w) = S$, say. The quantity of water is SX_d or FX_w.

Example 5. 100 kg/h of moist milk solids containing 10 wt% moisture (wet basis) is dried continuously to a final moisture content of 0.5 wt% using warm air of humidity 0.01 kg/kg (Fig. 2.13). The exit air humidity must not exceed 0.02 kg/kg dry air. Calculate the minimum air flowrate (dry basis) and the production rate of dried solids.

Basis: 100 kg/h moist solids.

The solution to this problem is simplified if it is recognized that the flows of dry solids and dry air (S and G kg/h respectively) do not change between the inlet and outlet of the dryer. We denote X_{in}

and X_{out} as the moisture contents of the inlet and outlet solids expressed in kg water/kg dry solids, and Y_{in} and Y_{out} as the humidities of the inlet and outlet air streams.

Now, since S and G are constant, a mass balance on water over the system gives:

$$S(X_{\text{in}} - X_{\text{out}}) = G(Y_{\text{out}} - Y_{\text{in}}) = M, \tag{2.13}$$

where M is the rate of transfer of water between the solids and the air.

From (2.12), the dry-basis moisture contents of the feed and product are:

$$X_{\text{in}} = 0.1/0.9 = 0.1111$$

and

$$X_{\text{out}} = 0.005/0.995 = 0.0050.$$

The dry solids flowrate is

$$S = 0.9 \times 100 = 90\,\text{kg/h}.$$

Therefore, the outlet flowrate of moist solids = $S(1 + X_{\text{out}})$ = 90 × (1.005025) = 90.45 kg/h
The moisture balance, (2.13), is thus:

$$90 \times (0.1111 - 0.0050) = G(0.02 - 0.01).$$

Hence

$$G = 954.8\,\text{kg dry air/h}.$$

2.3.1.10 Multistage Processes

Real processes rarely consist of a single piece of equipment—most production lines involve several interconnected units. Provided that all the input and output streams are identified correctly, the system boundary—and the mass and energy balances—need not be confined to a single operation. The system may be the whole process, or part of it. The system definition will depend on the objectives of the calculation and on the information available. To set up a mass balance over a complete process, it is often necessary to carry out detailed calculations over the individual units in the flowsheet.

To illustrate some of the methods involved in handling multistage processes, consider a simple extension of the previous example.

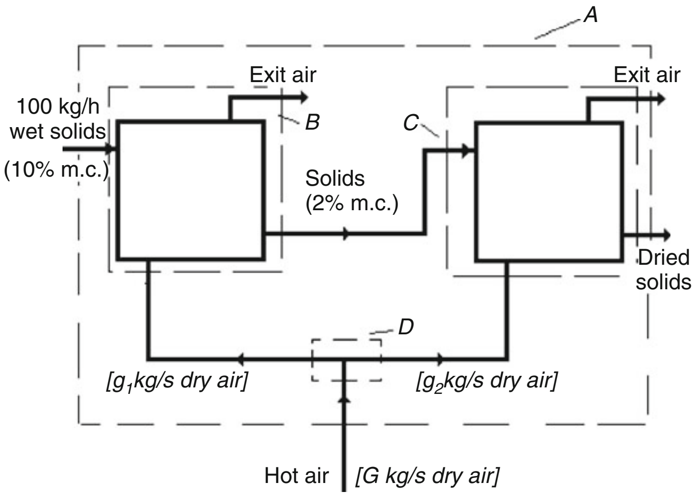
Example 6. Suppose that instead of carrying out the drying operation in a single dryer, the operation is carried out instead in two linked dryers, see Fig. 2.14. The intermediate solids moisture content is 2 wt% on a wet basis. The final solids moisture content is 0.5 wt%, as before. Calculate the air flows, if the exit air humidity from each unit is again 0.02 kg/kg.

Basis: 100 kg wet solids (as before) (i.e., 90 kg dry solids).

It is possible to define four system boundaries, as shown in Fig. 2.14:

(A) Around the whole process.
(B) Around the first unit.
(C) Around the second unit.
(D) Around the air stream feed split.

Fig. 2.14 Two-stage dryer



B, C and D can be thought of as subsystems of A.

Note that the overall system is exactly the same as in the previous example. The input and output flows of solids and gas are therefore the same as above. Since the moisture balance is unchanged we can immediately conclude from a balance over the stream split (D) that

$$g_1 + g_2 = G = 954.8\,\text{kg dry air/h}. \tag{2.14}$$

In order to calculate g_1 and g_2, it is now necessary to carry out balances over the sub-systems. Recall that, on a dry basis, the moisture content of the solids feed is 0.1111; the dry-basis moisture content of the intermediate solids stream is, from (2.12), 0.0204 on a fractional basis. A moisture balance over the first dryer, i.e., system boundary B, gives:

$$90 \times (0.1111 - 0.0204) = g_1(0.02 - 0.01)$$

so that

$$g_1 = 816.3\,\text{kg dry air/h}.$$

The air flow to the second dryer, g_2, can be obtained directly from the overall (air) balance around the split (D), (2.14), giving $g_2 = 138.4$ kg dry air/h.

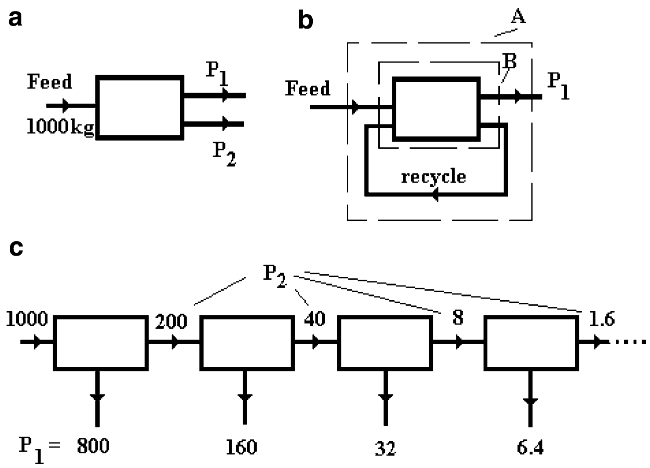
A moisture balance on the second drier is strictly redundant, but serves to check on the calculation:

$$g_2 = 90 \times (0.0204 - 0.0050)/0.01 = 138.4\,\text{kg dry air/h}.$$

The example confirms the obvious: provided the systems boundaries are correctly defined, the sum of the balances over the sub-systems must equal the balance over the whole system. This result applies equally to material and energy balances. Moreover, for a defined set of input/output conditions, the number (or indeed the type) of operations within the system boundary does not affect the overall balance. In the example above, as far as the overall balance is concerned, it is immaterial whether there are one, two, or more dryers.

In this example, the calculations were quite straightforward, since it was possible to complete the solution by marching forward from the inlet of the system. This may not always be possible when the plant is more complex or information is less well defined. As an example, we now consider systems with recycle.

Fig. 2.15 Recycle systems



2.3.1.11 Systems with Recycle

The ability to recycle material streams is very important in many processes. In general, the intention is to improve the process efficiency. For example, recycling may be used to recover and reuse raw materials that are not completely converted or to make better use of other process streams. Recycling of process streams and utilities is also a key element in strategies for waste minimization.

The principles can be explained by considering the hypothetical *continuous* food process shown in Fig. 2.15a where raw materials are transformed into the finished product P_1 and partially finished material P_2. The process efficiency is 80 %, i.e., 80 % of the feed is converted into product. Thus, for 1,000 kg feed the process gives 800 kg of product P_1 and 200 kg P_2.

Now suppose that all P_2 can be reworked into the product in the same machine, also with an efficiency of 80 %. Then a system with total recycle could be employed as shown in Fig. 2.15b.

The mathematics (i.e., mass balance) is deceptively simple. First we take a balance over the whole system, including the recycle loop, i.e., system A. Then

$$1{,}000 = P_1.$$

In other words, all the raw material is converted to product.

The question is then: how much material must be recycled per 1,000 kg feed? Call the recycle quantity R. Now assuming the same processing efficiency—i.e., 80 % of the total feed to the operation is converted to "useful" product—then a balance over system B gives:

$$P_1 = 0.8(1{,}000 + R) = 1{,}000. \tag{2.15}$$

So the recycle stream, $R = 250$ kg.

Note that the recycle stream is *not* the same as the "waste" stream in the system without recycle (i.e., 200 kg). This is because the system with recycle is *different* from the original system. In this analysis, it is assumed that the recycle is operating at steady state—it does not include the transient period during which steady state is reached.

One way of interpreting this particular result is to think of the process as one in which the by-product P_2 is successfully reworked into the product through an infinite number of reworking stages, each with an efficiency of 80 %, as shown in Fig. 2.15c.

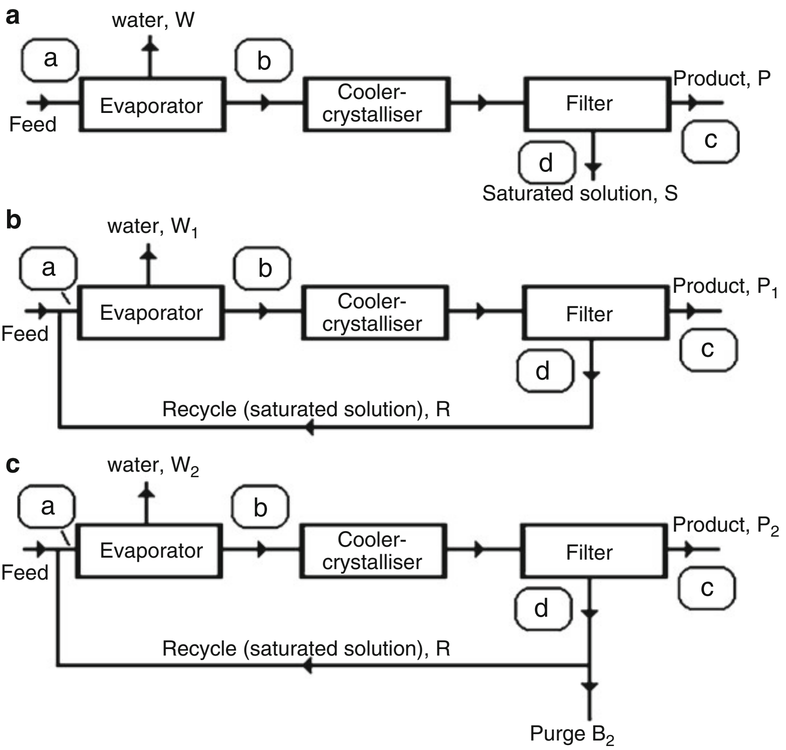


Fig. 2.16 Citric acid production

$$\text{The total amount of reworked product } (P_2) = 200 + 40 + 8 + 1.6 + \cdots \tag{2.16a}$$

and

$$\text{The total amount of product } (P_1) = 800 + 160 + 32 + 6.4 + \cdots \tag{2.16b}$$

In fact, both these series converge: the total reworked product

$$= 200(1 + 0.2 + 0.22 + 0.24 + \cdots) = \frac{200}{1 - 0.2} = 250\,\text{kg} \tag{2.16c}$$

and, from (2.16b), the total product $P_1 = 1{,}000$ kg.

There are limits to the amount of reworking that can be achieved in practice. One reason is that the efficiency of conversion falls with increased reworking; another is the possible buildup of unwanted or even dangerous components. This is why recycling in agricultural and food systems must always be pursued with a good deal of caution.

Example 7. To recover citric acid from a fermentation broth, the acid is evaporated from a concentration of around 10–40 wt%, followed by crystallization at a lower temperature where the saturation concentration is around 2 wt% citric acid, and subsequent filtration. This is shown in Fig. 2.16a. What recycle options are available to increase the yield?

The slurry of citric acid crystals and saturated solution is separated by filtration. Since the latter stream still contains some citric acid, further recovery by recycling is clearly a possibility. Indeed, if there were no components other than citric acid and water in this stream, total recycle could be employed (Fig. 2.16b). However, if the stream contained another nonvolatile component, total recycle could not be employed since this component would build up in the system until it contaminated the product itself. In this case, either some means of separating the contaminant or of controlling its buildup in the system must be found. The easiest way of limiting the buildup is by adding a controlled purge or bleed to the recycle, as shown in Fig. 2.16c.

We now establish mass balances over these flowsheets and compare the consequences for process efficiency.

Consider a plant where the feed rate to the process is 5,000 kg/day. The mass fraction of citric acid in the aqueous feed is 0.1; the mass fraction in the stream leaving the evaporator (i.e., at "b") = 0.4 and the mass fraction in the saturated solution leaving the filter is 0.02. We also assume that the citric acid crystals in the product stream are pure and bone dry.

Take as basis one day's operation, i.e., $F = 5{,}000$ kg.

1. System Without Recycle (Fig. 2.16a):
   Since the compositions of the streams at "a" and "b" are known, we first set up a mass balance over the evaporator. Let B = total flow of the stream at "b":

   Given the data on flows and compositions, we can write three balance equations over the evaporator. Since there are two components (citric acid and water), only two are independent:

$$\text{Water}: \quad 4{,}500 = W + 0.6B. \tag{2.17}$$

$$\text{Citric acid}: \quad 500 = 0.4B. \tag{2.18}$$

$$\text{Total} \quad 5{,}000 = W + B. \tag{2.19}$$

   Solving any two from these gives

$$B(\text{stream to crystallizer}) = 1{,}250\,\text{kg}.$$

$$W(\text{water evaporated}) = 3{,}750\,\text{kg}.$$

   Having solved for stream B, a mass balance over the cooler-crystallizer and the filter together can be established. Here we use the fact that stream S contains 2 % citric acid and 98 % water. These are, for each component and the total flows, respectively:

$$\text{Citric acid}: \quad 0.4B = 500 = P + 0.02S. \tag{2.20}$$

$$\text{Water}: \quad 0.6B = 750 = 0.98S. \tag{2.21}$$

$$\text{Total} \quad B = 1{,}250 = P + S. \tag{2.22}$$

   From which:

$$S = 765.3\,\text{kg}.$$

$$P = 484.7\,\text{kg}.$$

   The overall yield of citric acid is therefore 100 × 484.694/500 = 96.94 %.

2. System With Total Recycle (Fig. 2.16b):
   The problem here is that the recycle flow, R, is not known. The values of W_1 and P_1 are also different from their values in the first example. However, they can be obtained directly from an overall mass balance.

Overall balances on the two components are, respectively:

$$\text{Citric acid :} \quad 500 = P_1. \tag{2.23}$$

$$\text{Water :} \quad 4{,}500 = W_1. \tag{2.24}$$

These clearly also satisfy the total balance.

We can immediately conclude that it is possible, using total recycle, to recover 100 % of the citric acid. Note that the price paid for this includes larger and more complex equipment, and increased energy use, since all the water in the feed is now evaporated, compared with the 3,750 kg evaporated in the system without recycle.

In order to estimate the recycle flowrate, it is necessary to carry out one or more internal balances. In general there are two ways of proceeding. The first, which is employed in many computer-aided design packages, is to use a trial and error or "tearing" algorithm. The second, which is sometimes possible with relatively simple problems, is to find an algebraic solution. Both methods are illustrated here.

Trial and Error: "Tearing"

In this example, although the composition of the recycle stream is known (it is saturated with citric acid, and therefore contains 2 % acid and 98 % water), its magnitude is not known. A process of trial and error, based on an initial guess for the value of R is used to converge on the true value. It will clearly be different from the value of the waste stream S in the first example, but presumably it should be of a similar order of magnitude.

We therefore assume a first estimate for $R = 750$ kg. Given this estimate, and knowing its composition we can calculate the flow and composition of the stream at "a," the inlet to the evaporator. Balances on citric acid and water give the composition of stream "a" shown in Table 2.5a.

Since 4,500 kg of water is evaporated, the composition of stream "b" is as given in Table 2.5b. However, stream "b" should contain 40 % citric acid, rather than 41.2 %. This means that our estimate of R was wrong. As a second estimate try $R = 800$ kg. Proceeding as before, we obtain the corresponding results shown in Table 2.5c, d; these indicate that the second estimate for R is slightly too high. Linear interpolation suggests that the next estimate should be

$$R = 800 - (40 - 39.69) \times 50/(41.2 - 39.69) = 789.7\,\text{kg}.$$

With this value we obtain the results shown in Table 2.5e, f. The calculated value of the citric acid content of stream "b" is now acceptably close to the target value.

This procedure is called tearing, since it can be interpreted as "tearing" one of the streams, estimating its value and then computing around the flowsheet to see if the values correspond. Here, as shown in Fig. 2.17, the calculation starts at point "e" and is be carried through to "d," at which point in the flowsheet the values should coincide.

In this case, it was not necessary to complete the calculation in order to arrive at a good estimate for R. However, for good measure, the whole procedure with $R = 789.7$ kg/h is summarized in Table 2.5g. This shows that the contents of streams "e" and "d," on either side of the torn stream, do coincide. Note that this type of calculation is easily performed using for example the Solver routine in MS Excel.

Table 2.5 Mass balances for Example 7(a)

Component	kg	wt%
(a) ($R = 750$ kg)		
Citric acid	$500 + 0.02 \times 750 = 515$	8.957
Water	$4{,}500 + 0.98 \times 750 = 5{,}235$	91.043
Total	$F + R = 5{,}750$	100
(b)		
Citric acid	515	41.2
Water	735	58.8
Total	1,250	100
(c) ($R = 800$ kg)		
Citric acid	$500 + 0.02 \times 800 = 516$	8.897
Water	$4{,}500 + 0.98 \times 800 = 5{,}284$	91.103
Total	$F + R = 5{,}800$	100
(d)		
Citric acid	516	39.69
Water	784	60.31
Total	1,300	100
(e) ($R = 789.7$ kg)		
Citric acid	$500 + 0.02 \times 789.7 = 515.79$	8.909
Water	$4{,}500 + 0.98 \times 789.7 = 5{,}273.91$	91.091
Total	$F + R = 5{,}789.7$	100
(f)		
Citric acid	515.79	39.999
Water	773.91	60.001
Total	1,289.7	100

(g) (Summary)

Component	Stream at "e"	Stream at "a"	Stream at "b"	Stream at "d"
Citric acid	15.79	515.79	515.79	15.79
Water	773.91	5,273.91	773.91	773.91
Total	789.7	5,789.7	1,289.7	789.7

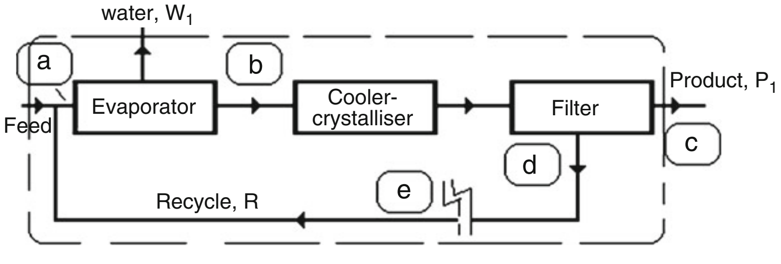


Fig. 2.17 Citric acid production: "tearing"

Analytical Solutions

In some relatively simple problems with recycle, particularly when the number of components is small, it is possible to solve problems like the one above directly. Instead of guessing the value of the recycle flowrate, R, and iterating until the solution converges, the problem is converted into algebraic form in order to solve for R. As above, the solution starts at point "e". Since the composition is known at this point (2 % citric acid and 98 % water) the second column in Table 2.6 can be

Table 2.6 Mass balances for Example 7(b)

Component	Stream at "e"	Stream at "a"	Stream at "b"
Citric acid	$0.02R$	$500 + 0.02R$	$500 + 0.02R$
Water	$0.98R$	$4{,}500 + 0.98R$	$0.98R$
Total	R	$5{,}000 + R$	$500 + R$

completed directly. The entries in the third column (at "a") then follow directly from a mass balance over the mixing point, and the entries in the fourth column—the stream leaving the evaporator—follow from a mass balance over this unit. Since the citric acid must comprise 40 % of stream "b," it follows that

$$500 + 0.02R = 0.4(500 + R) = 200 + 0.4R. \tag{2.25}$$

This yields:

$$R = 300/0.38 = 789.5\,\text{kg}.$$

In this example, the feed stream is unlikely to comprise only citric acid and water. Suppose this stream contains 1 % citric acid, 0.5 % contaminants and 98.5 % water. An immediate consequence is that operation with total recycle is no longer possible, since the contaminant would build up continuously in the system. In practice there will usually be some constraint on the permitted buildup of contaminant. Let us suppose that it should not exceed 5 % in the recycle stream. The strategy to control this level will be to introduce a controlled purge or bleed stream from the system.

We assume that no contaminant leaves with evaporated water or with the citric acid product. The obvious stream to purge is the saturated citric acid stream leaving the filter, i.e., stream "d". The purge system is shown in Fig. 2.16c.

The introduction of the purge stream changes the overall balances to

$$\text{Citric acid}: \quad 500 = P_2 + 0.02B_2. \tag{2.26}$$

$$\text{Contaminant}: \quad 25 = 0.05B_2. \tag{2.27}$$

$$\text{Water}: \quad 4,475 = W_2 + 0.93B_2. \tag{2.28}$$

$$\text{Total} \quad 5,000 = P_2 + B_2 + W_2. \tag{2.29}$$

Note that, having fixed the level of the contaminant in the recycle and purge, the purge rate is fixed since, from (2.27), $B_2 = 500$ kg. The complete solution to the equation set above is:

$$B_2 = 500\,\text{kg}.$$

$$P_2 = 490\,\text{kg}.$$

$$W_2 = 4,010\,\text{kg}.$$

The purge stream and the recycle have the same composition, viz. 2 % citric acid, 5 % contaminant, 93 % water.

Proceeding as before, mass balances on the mix between the fresh feed and the recycle and then over the evaporator (where 4,010 kg of water are evaporated) give the results shown in Table 2.5b. The citric acid concentration in the exit stream from the evaporator is 40 % so that

$$500 + 0.02R = 0.4(990 + R)$$

or

$$R = 273.7\,\text{kg}.$$

The complete mass balance around the flowsheet is summarized in Table 2.6 (all numbers in kg), where the final column serves as a check on the second.

It should be clear from this example that, since the level of contaminant directly controls the purge rate, this also therefore influences the recovery of pure product (in stream *P*). There is always a trade-off between the level of recycle and the overall process efficiency.

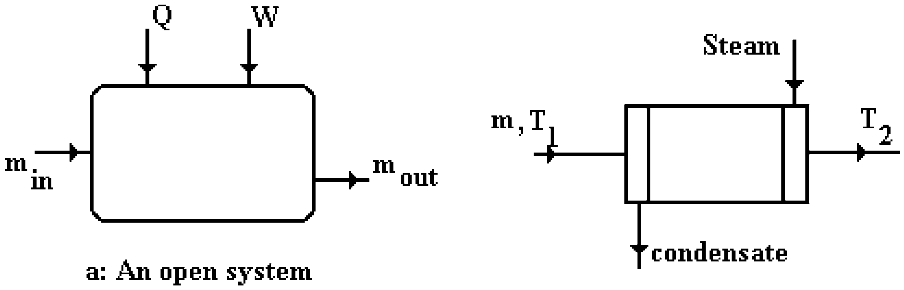
2.3.2 Energy Balancing

The economic and environmental costs of energy use in the food processing industry are extremely important. The carbon tax levy puts even greater pressure on the industry to minimize energy use and to optimize its use over time across the whole operation. To begin to address this problem it is necessary to be able to estimate the heating or cooling requirements for typical operations such as thermal processing, cooling and freezing, mixing, etc. operations. This, together with information on the scheduling of operations, provides the basis for addressing problems such as: “Is a particular method of heating or cooling the best option?” o*r* “How can the overall energy efficiency of the process be maximized?” To answer the first sort of question, we rely principally on the first law of thermodynamics: the statement that energy is conserved. To answer the second, we often need to draw on the second law. Here we will concentrate mainly on the first type of question, whilst introducing some approaches to the second.

First we must clarify what we mean by energy and how it is measured. In the SI system, the unit of force (dimensions: mass times acceleration) is the Newton (N) defined as 1 kg m/s^2. The most familiar definition of energy is that in a mechanical system: it is the force applied times the distance moved. Energy or work thus has units of Newton meters or joules (J) where 1 J = 1 N m. This applies to any form of energy. For example, an apple of mass 100 g held stationary 10 m above the ground has a potential energy of 9.81 J. Note that it is necessary to define a datum level—the ground. If some other reference or datum level had been chosen, the energy of the object would of course be different. Power, which is defined as the *rate of doing work*, is measured in watts where 1 W = 1 J/s.

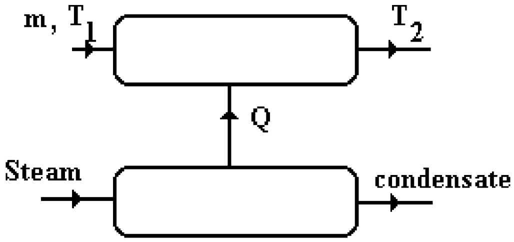
Of course, materials have energy because of other attributes: their velocity, temperature, pressure, physical state (solid, liquid, or gas), and chemical composition all contribute to their energy (or ability to do work). It is always important to define datum levels unambiguously; energy is always a function of state and calculations should always use the same reference level (i.e., where the energy level is arbitrarily taken to be zero). It is also important to work in consistent units: then the question of the energy source is irrelevant in the energy balance (but not its efficiency or cost).

Whilst energy is conserved, its value changes because it is transferred or converted from one form to another. In mixing, for example, the shaft power is converted into motion and, ultimately, through friction and viscosity, into heat. The second law states effectively that heat can only be transferred down a temperature gradient. Thus, the heat carried away from a process vessel by cooling water is always at a lower temperature—and therefore is less valuable in its capacity to do useful work—than the vessel contents. In other words, the quality of heat energy depends on its temperature and this must be accounted for in any analysis of energy efficiency. It requires ingenuity and money to upgrade its quality. Also, keep in mind that in the real world many energy



a: An open system

b: Steriliser



c: Steriliser as two open systems

Fig. 2.18 Open systems

transformation processes are irreversible: heat released from the mixer cannot be used to unmix the dough.

In order to apply the first (and second) law to any real situation, it is important to have a clear definition of the system over which the balance is made. We must also differentiate between *closed* systems and *open* systems. A batch dough mixer is an example of a *closed* system: the only transfers of energy across its boundary during operation are in the nonmaterial forms of heat and shaft power. On the other hand, a continuous steam sterilizer is an open system since energy is transported into and out of the process, and used at the same time, by the process liquid and the steam and condensate (Fig. 2.18).

For a closed system, application of the first law is very simple. Consider a process operated over a given time interval in which the total *net* flows of heat and work are Q and W. (If a process picks up 5,000 kJ of heat from a steam supply and at the same time loses 500 kJ to the environment, the net flow of heat is 4,500 kJ). We define both Q and W to be positive for flows *into* the system.

Then the increase (decrease) in energy stored in the system must, because of conservation, equal the net transfer of energy into (out of) the system, or:

$$\Delta E = Q + W. \tag{2.30}$$

This equation will be in joules or kilojoules.

If ΔE is not zero then the final system contents must differ from the starting contents in some way, e.g., by changes in composition, temperature, physical state or internal surface area. For example, if an operation simply involved stirring and heating a liquid, the increase in energy would be entirely accounted for by an increase in temperature. In the case of a dough maker, however, the energy transferred through mixing would be used to drive chemical and physical changes as well as increasing the temperature. Clearly, (2.30) is only really useful when ΔE can be related to these physical and chemical changes.

Equation (2.30) can also be written in terms of the *rates* of energy change and transfer so that instantaneously

$$\frac{\mathrm{d}E}{\mathrm{d}t} = q + W, \tag{2.31}$$

where q and W are the net *rates* of energy and work input into the system. Equation (2.31) is thus a power balance, normally having the units of watts or kilowatts.

In the more general case of an open system we must allow for the energy transported in to and out of the system by the material flows, together with the "flow" work they generate. To set up equations similar to those for the closed system, we use the symbol M to represent the mass transferred by a particular stream of material; Q and W represent the total (net) quantities of heat and work added to the system over a period of time; alternatively, m represents the mass flowrate; q and w are the net rates of heat and work input (i.e., power as heat and mechanical energy).

Since energy cannot disappear, the *net* change in stored energy within the system boundary over a given period of operation must exactly balance the net energy input by heat and work and the net energy difference between all the inflowing and outflowing streams. For a process involving only one stream with energy/kg E_{in} and E_{out} respectively at the entry and exit from the system (where the energy levels are defined with reference to consistent datum levels), the energy balance is:

$$\Delta E = Q + W + (ME)_{\mathrm{in}} - (ME)_{\mathrm{out}}, \tag{2.32}$$

where ΔE is the *change* in stored system energy over the operating period in question. Alternatively, in terms of rates:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = q + w + (mE)_{\mathrm{in}} - (mE)_{\mathrm{out}}. \tag{2.33}$$

These equations are easily generalized to systems with many input and output streams by adding the appropriate "*mE*" or "*ME*" terms.

These equations represent the balances over an unsteady open system—unsteady because they include the possibility of changes in the stored energy of the system with time. However, once the system *has achieved a steady state* in which all flows and temperatures are independent of time, the stored energy is then constant and the energy balance equations become respectively:

$$Q + W + (ME)_{\mathrm{in}} - (ME)_{\mathrm{out}} = 0 \tag{2.34}$$

and,

$$q + w + (mE)_{\mathrm{in}} - (mE)_{\mathrm{out}} = 0, \tag{2.35}$$

which are the general equations for a *steady open* system.

2.3.3 *Stored and Internal Energy: Enthalpy*

2.3.3.1 Single Components

As noted earlier, the energy of a process stream includes contributions from a variety of sources such as kinetic and potential energies, surface energy, the temperature, composition, physical conditions and state of the stream, etc. In any particular situation, the changes in many of these terms are negligible: for example in situations involving only a single phase, interfacial forces can be forgotten. In heat exchangers, the changes in kinetic and potential energies are negligible, and so on. It is important to remember that all the contributions must be measured with respect to a defined but usually arbitrary datum.

In many applications, we use the *enthalpy*, or more correctly specific enthalpy, of a component or mixture of components as the measure of its energy content (the term *specific* is used to denote "per unit mass"). Enthalpy is the sum of:

- Internal energy U (reflecting temperature, physical state, etc., in relation to a defined datum and measured in J/kg or kJ/kg).

  and

- A "flow work" term, pV (where p is pressure and V specific volume, which is the reciprocal of the density ρ), also in J/kg or kJ/kg.

  Thus

$$h = U + pV = U + p/\rho. \tag{2.36}$$

The heat content of m kg of a material with specific enthalpy h kJ/kg is simply $m.h$ kJ. Values of h for pure components are easily calculated or can be found from tables. For example, the steam tables tabulate the enthalpies of water (liquid and vapor) over a wide range of conditions relative to water at its triple point (essentially 0 °C). Such tables can be found in for example Green and Perry (2008) and also in most thermodynamics texts. The thermodynamic properties of food materials are less complete, but there are several good sources (see, e.g., Sahin and Sumnu 2006; Rahman 2009). The rules for mixtures (see Sect. 2.3.3.2) are often useful in food calculations.

Note also that for liquids and solids under "normal" processing conditions, the enthalpy and internal energy values are almost the same, and enthalpy values can be used in rough calculations without serious error. This is *not* true for gases and vapors where compressibility implies that the enthalpy is always measurably greater than the internal energy.

For a steady *open* system, the integrated form of the first law becomes

$$Q + W + (Mh)_{\text{in}} - (Mh)_{\text{out}} = 0 \tag{2.37}$$

and for a *closed* system:

$$Q + W = M[U_{\text{final}} - U_{\text{start}}], \tag{2.38}$$

where M is the total mass inventory of the system. Thus, for solids and liquids we can write:

$$Q + W = M[h_{\text{final}} - h_{\text{start}}]. \tag{2.39}$$

Often, changes in enthalpy are mainly due to changes in heat content, in particular, from a change in temperature (so called "sensible" heat) and/or from a phase change which, although isothermal, involves a "latent" heat. Thus, the enthalpy of a pure component at T_2 with reference to (itself in the same physical state at) T_1 is:

$$h_{21} = \int_{T_1}^{T_2} C_{\text{p}} \mathrm{d}T = C\text{p}_{\text{m}}(T_2 - T_1), \tag{2.40}$$

where $C\text{p}_{\text{m}}$ is the mean heat capacity between T_1 and T_2.

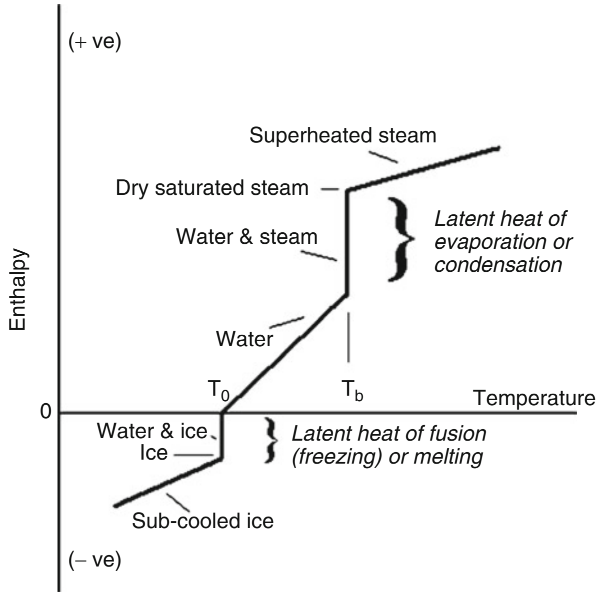


Fig. 2.19 Enthalpy–temperature diagram

For example, liquid water has a mean heat capacity of 4.19 kJ/kg K over the range 0–100 °C; taking its enthalpy to be zero at 0 °C, the enthalpy of water at 80 °C is thus approximately 80 × 4.19 = 335.2 kJ/kg (this is within 1 % of the accurate value given in steam tables). The energy to heat 100 kg of water from 25 to 80 °C is, from the first law (2.37):

$$Q = 100 \times 4.19 \times (80 - 25) = 23{,}045\,\mathrm{kJ}.$$

(Note that this assumes that the mean heat capacity is constant; it isn't but the errors involved here are small).

A phase change at a given temperature and pressure requires or liberates a quantum of energy—the (specific) latent heat. For example, 334 kJ heat must be removed to freeze 1 kg water at 0 °C; to boil water at 100 °C requires 2,257 kJ/kg of water evaporated. Thus, the enthalpy of ice at 0 °C is lower than the enthalpy of water at the same temperature by the latent heat of fusion (i.e., freezing); the enthalpy of steam is greater than the enthalpy of liquid water at its boiling point by the latent heat of evaporation. It is interesting to note that it should require less energy to concentrate a liquid such as fruit juice by freezing rather than evaporation. Whilst true, practicalities intervene—it is more complex to design efficient systems operating below ambient temperatures and carryover of fruit into the ice phase is also a problem.

For a single, pure component the above discussion can be generalized. We take the enthalpy datum to be T_1, liquid phase. Suppose the component evaporates at T_2 and is then superheated to T_3. We also assume the mean heat capacities of the liquid and vapor over the temperature ranges in question to be C_f and C_g respectively; then the enthalpy at T_3, h_{31}, is:

$$h_{31} = C_\mathrm{f}(T_2 - T_1) + h_{\mathrm{fg},2} + C_\mathrm{g}(T_3 - T_2). \tag{2.41}$$

The steam tables record values of h_f, h_fg, and h_g for dry, saturated and superheated steam. Note that h_g is defined relative to the triple point. Figure 2.19, a qualitative enthalpy–temperature diagram for water (at constant pressure), illustrates the principles involved in determining the enthalpy of a pure substance as it goes through phase and temperature changes. The datum level is taken as the freezing point T_o. The boiling point is T_b.

Because energy and enthalpy are state functions, the final enthalpy in (2.41) is independent of the path between the reference at T_1 and the final state at T_3; in other words the temperature T_2 need not correspond to the actual temperature at which the phase change occurs.

To a very rough approximation, the enthalpy of many dilute liquid streams can be assumed to be close to that of water at the same temperature. This assumption is reasonable during the early stages of design; it should not be made during detailed calculations.

2.3.3.2 Mixtures

In practice most process streams comprise mixtures of components, whether dissolved or suspended. Sometimes these mixtures are far from ideal, so that enthalpy and other data must be gathered from the literature or measured directly. Often, a reasonable first approximation in food and bioprocessing is to assume ideal behavior, i.e., that *the enthalpy of a mixture is the weighted sum of the specific enthalpies of the various components*. This assumption breaks down where there are strong solutions, etc. Three effects in particular can invalidate the assumption of ideality: heat effects due to dissolution, mixing and dissociation. In many cases it is reasonable and justifiable for the purposes of establishing an energy balance to treat a complex stream as if were a single component with empirically determined physical and thermodynamic properties.

2.3.3.3 Biochemical Reactions

So far this discussion has been concerned with essentially physical changes. There are many situations where chemical or biochemical changes occur. We consider briefly how the treatment may be extended to cover such eventualities.

Consider an energy balance about a bread-baking line. We start with the dough mixer. Suppose the datum level is taken as the raw material ingredients (flour, fat, water, etc.) at 0 °C. The materials fed to the dough mixer will then have positive enthalpy values because their temperatures are generally greater than the datum. At the end of the dough-making cycle, the dough also has a positive "sensible" enthalpy by virtue of its temperature, but its enthalpy must also reflect the fact the dough is not simply an ideal mixture of the raw ingredients. In practice some of the energy input into the mixer goes into the creation of chemical bonds, and this is reflected in the enthalpy of the dough.

In principle, food and biological operations can be handled in just the same way as chemical reactions for which the necessary thermodynamics is well established. In practice, just as with mixtures, many unknown transformations may occur, in which case the process can be handled as a pseudo-reaction (which is useful in fermentation processes); alternatively it may be possible to identify the most important or limiting processes to help quantification. Many food operations are dominated by work (mechanical power) and thermal effects: the thermodynamics of the "reactions" involved in bread making, for example, are totally swamped by heat effects.

To set up the energy balance to include the effects of reactions and mixing (where these generate or require heat), it is best to choose the input raw materials as the datum level. Thus, to continue the qualitative discussion of dough mixing:

- The enthalpy of the input stream(s) is the sum of the sensible enthalpies of all the feed materials—i.e., allowing for temperature and possibly phase changes from the standard state taken as datum.
- The enthalpy of the output stream(s) has two additive components: the sensible enthalpy, which measures the enthalpy of the output materials with respect to themselves at 25 °C, and the

enthalpy of the output compounds at 25 °C with respect to the feed materials also at 25 °C. This second term would include the standard heats of reaction and mixing if these are significant.

For a single reaction in which x kg of product are formed and ΔH is the heat of reaction and/or mixing per kg product, the overall energy balance has the form:

$$\sum (mh)_{\text{inputs}} + q + w = x\Delta H + \sum (mh)_{\text{outputs}}, \tag{2.42}$$

where the enthalpies are measured/calculated from the same compound at 25 °C as the datum (i.e., the h terms are the "sensible" enthalpies).

Since this equation is written in terms of flowrates, q and w will be in kW; the balance can of course be written in terms of quantities in which case Q and W will be in energy units.

Note that the equation reduces to the earlier balances for non-reacting systems when the "$x\Delta H$" term is negligible. Note, too, that in many food processes—dough mixing, food extrusion, and fermentation, for example, the work input term (w) in the energy balance is highly significant.

2.3.4 *Examples of Energy Balance Calculations*

2.3.4.1 Continuous Heat Exchangers

Consider the continuous heat exchanger shown in Fig. 2.20. Assuming that the heat losses and work done on the systems are negligible, writing the energy balance (2.35) in terms of rates gives:

$$\sum (mh)_{\text{in}} - \sum (mh)_{\text{out}} = 0 \tag{2.43}$$

where "Σ" denotes "the sum of". Since there are only two streams (labeled "1" and "2"), this becomes:

$$m_1\left(h_{1,\text{in}} - h_{1,\text{out}}\right) = m_2\left(h_{2,\text{out}} - h_{2,\text{in}}\right) = Q, \tag{2.44}$$

i.e., the *change* in enthalpy of one stream exactly balances the other. Note that Q is the rate of heat transfer between the two sides of the exchanger. It is also known as the heat load.

Assuming no phase changes and that the streams have constant heat capacities $C\mathrm{p}_1$ and $C\mathrm{p}_2$, (2.44) becomes:

$$m_1 C\mathrm{p}_1 (T_{\text{in}} - T_{\text{out}}) = m_2 C\mathrm{p}_2 (\Theta_{\text{out}} - \Theta_{\text{in}}) = Q. \tag{2.45}$$

2.3.4.2 Evaporators

Figure 2.20 also illustrates a simple continuous evaporator. Process liquid entering at T_{i} is heated to its boiling point T at the operating pressure P; vapor and concentrated liquid also leave at T. Heat is supplied by condensing saturated steam at flowrate S and temperature T_{s}. Again assuming no subcooling, an energy balance over the evaporator implies that the loss of enthalpy on the steam side must be balanced by the increase in enthalpy on the process side, viz.:

$$Sh_{\mathrm{fg},T_{\mathrm{s}}} = Vh_{\mathrm{g},T} + Lh_{\mathrm{f},T} - Fh_{\mathrm{f},T_{\mathrm{i}}}. \tag{2.46}$$

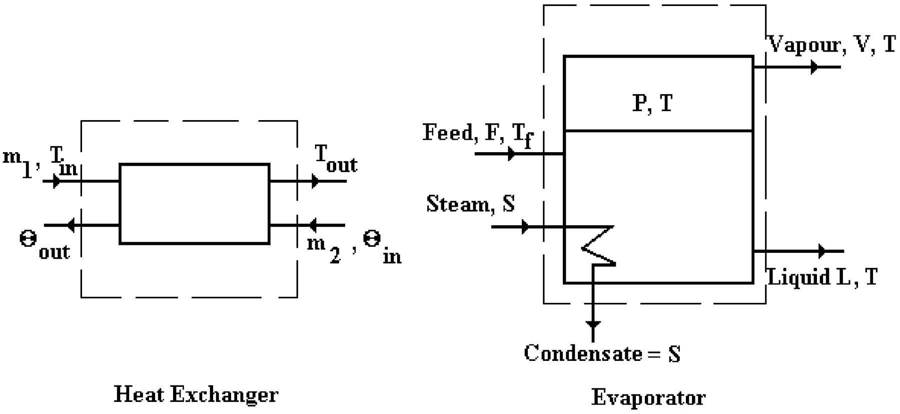


Fig. 2.20 Heat exchange and evaporation

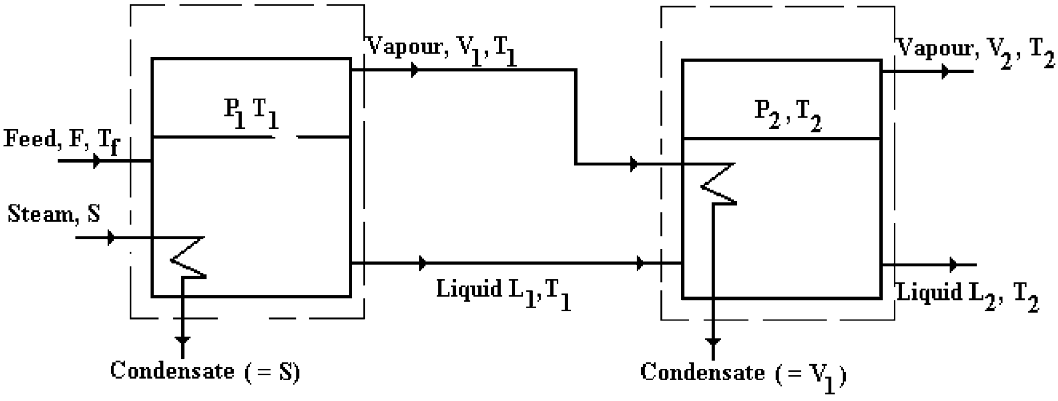


Fig. 2.21 Two-stage evaporator

For a liquid with constant mean specific heat capacity C_p this reduces to

$$Sh_{\mathrm{fg},T_\mathrm{s}} = VC_\mathrm{p}T + Vh_{\mathrm{fg},T} + LC_\mathrm{p}T - FC_\mathrm{p}T_\mathrm{i}. \tag{2.47}$$

where $h_{\mathrm{fg},T}$ and $h_{\mathrm{fg},T_\mathrm{s}}$ denote the latent heat at T and T_s, respectively.

The process flows are also linked through the overall mass balance:

$$F = V + L. \tag{2.48}$$

Since the latent heat of evaporation of water is high the "Vh_fg" term always dominates the right hand side of the energy balance, (2.47); V is thus similar in magnitude to, but always smaller than, the steam flow S. With an idealized evaporator, 1 kg of steam produces around 1 kg of vapor. In practice, the ratio is more likely to be around 0.6–0.8.

This is the motivation for multi-effect evaporation. Figure 2.21 shows a two-stage forward feed evaporator: vapor from the first "effect" is used as the heat supply to the second. The temperature (and therefore the pressure) in the first effect must, of course, be higher than the temperature in the second effect if heat is to be transferred to the second stage. Here 1 kg of steam fed to the first effect produces almost twice as much vapor as in the single effect system. Each additional effect improves the energy efficiency whilst, of course, adding to the investment costs. The optimum is where the benefits and costs balance.

Example 8. Consider an evaporator designed to raise the solids content of a milk stream from 5 to 10 %. Assume that the milk is fed at 12 °C, that evaporation takes place at 50 kPa (approximately 0.5 atm), and that the process streams have the same thermodynamic properties as water. From steam tables, the milk boils at 81.3 °C. The energy supply is dry saturated steam at 800 kPa (170 °C), with latent heat $h_{fg} = 2{,}048$ kJ/kg.

Take the basis of the calculations as 100 kg milk feed. The flowrate of liquid leaving the evaporator is $L = 100 \times 5/10 = 50$ kg and, from the overall mass balance, $V = 50$ kg.

Taking enthalpy values from steam tables, the energy balance (2.47) becomes:

$$S \times 2,048 = 50 \times 341.3 + 50 \times 2,304.1 + 50 \times 341.3 - 100 \times 48.8$$

or

$$S = 70.5\,\text{kg}.$$

Example 9. We consider the milk processing line shown in Fig. 2.2 and aim to calculate the cooling and heating requirements for the cooler, the storage tank and the pasteurizer. In addition to the plant items shown, a cooler operates on the pasteurizer discharge.

The following conditions are assumed:

Tanker capacity: 10 t milk.
Milk delivered at 10 °C.
Time to discharge milk to storage = 20 min.
Milk to be cooled to 4 °C.
Coolant: glycol solution at −10 °C; maximum temperature to be −5 °C.
Storage conditions: milk at 4 °C. Heat losses to environment average 5 kW.
Time to process batch through pasteurizer: 30 min.
Pasteurization temperature = 70 °C.
Pasteurizer heated (indirectly) by dry saturated steam at 180 °C.
Final delivery temperature of milk from pasteurizer = 5 °C.

In addition:

Assume mean heat capacity of milk = 4.2 kJ/(kg K).
Assume mean heat capacity of glycol solution = 3.5 kJ/(kg K).
Neglect heat losses from the cooler and pasteurizer.
Neglect subcooling of steam (i.e., condensate leaves at 180 °C).

From steam tables the properties of steam at 180 °C are:

$h_f = 763.1$ kJ/kg.
$h_{fg} = 2{,}014.9$ kJ/kg.
$h_g = 2{,}778$ kJ/kg.

In practice, some preliminary cooling (in the first stage) and heating (in the pasteurizer) are needed to reach steady state. We neglect these effects and assume steady-state behavior throughout. The material balance is trivial: neglecting losses in the system, the total quantity of milk processed is 10 t.

The datum level for the energy balance calculations is liquid water and milk at 0 °C. We can establish the energy balance over each plant item in turn.

1. *Cooler*
   All the heat lost by the milk is transferred to the glycol; there are no additional heat or work inputs to the system. Let G = glycol flowrate. Then the average energy (power) balance (2.45) becomes:

   $$(10{,}000 \times 3/3{,}600) \times 4.2 \times (10 - 4) = G \times 3.5 \times 5 = \text{Heat load} = 35\,\text{kW},$$

   and $G = 2$ kg/s, i.e., 7.2 t/h. Assuming a batch discharge time of 20 min, this corresponds to a total glycol flow of 2.4 t. The refrigeration system required to maintain the glycol temperature at −10 °C would therefore need a capacity of at least 40 kW for steady operation. In practice the maximum rating would be considerably greater than this to permit rapid start up, etc.
2. *Storage tank*
   A further 5 kW cooling capacity would be needed (on average) to maintain the milk temperature during storage.
3. *Pasteurizer*
   Let S = steam flowrate (kg/s).
   The energy balance is given by (2.46). The heat load on the system is:

   $$10{,}000/(0.5 \times 3{,}600) \times 4.2 \times (70 - 4) = S\left(h_{\mathrm{g}} - h_{\mathrm{f}}\right) = Sh_{\mathrm{fg}} = S \times 2{,}014.9.$$

   $$= 1{,}540\,\text{kW}(\text{for } 30\,\text{min})$$

   $$\text{and } S = 0.764\,\text{kg/s or } 2.7\,\text{t/h}.$$

   The total steam requirement per batch is thus 1.376 t, corresponding to a total heat load of 2.77 MJ.
4. *Cooler*
   There are two possibilities. One is to use glycol from the refrigeration circuit. The other is to use cooling water (typically at 15–18 °C) to reduce the temperature to around 25 °C and then to further cool the stream using glycol to the desired temperature. The total heating load will be the same in both cases: the problem is essentially economic (cooling water being cheaper than refrigerant).

In either case the total heat to be rejected by the cooling system = 10,000 × 4.2 × (70 − 5) = 2.6 MJ. (This, of course, is almost the same as the heat added to the system by the steam.)

Even if there are no other process units involved in the factory, the flowsheet used in this problem is very inefficient from an energy conservation point of view. This refers particularly to the pasteurization/cooling system since the energy transferred from the steam is rejected into the cooling water and/or glycol at a low temperature with no attempt at recovery. A more efficient scheme might be to use the warm milk stream leaving the pasteurizer to heat up the incoming feed. In practice it would be uneconomic to try to raise the temperature to more than about 55 or 60 °C since this would imply a very large heat exchanger. The flowsheet in Fig. 2.22 shows how this might be achieved. Assume that the milk feed is preheated to 60 °C in the first heat exchanger. The heat load on this exchanger is thus (10,000 × 3/3,600) × (60 − 4) × 4.2 = 1,960 kW, which is supplied by the warm milk. Since the same process liquid is being used to heat itself (i.e., the mass flowrate and thermal properties are the same on both sides of the heat exchanger), the warm milk must cool down by exactly the same amount as the cold stream warms up—i.e., to 14 °C.

The steam requirements in the pasteurizer are now greatly reduced, since the heat load is reduced in the ratio 10/66, giving a steam requirement of 0.417 t/h and a total requirement of 0.21 t. The cooling requirements are also dramatically reduced.

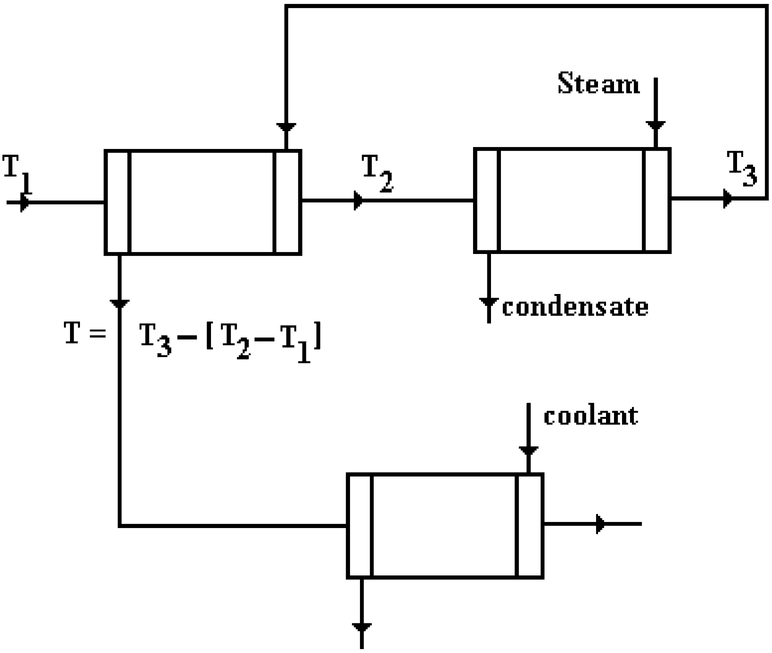


Fig. 2.22 Pasteurizer with heat recovery

In practice, the limitation on efficiency is economic, stemming from the second law of thermodynamics. For heat transfer there must always be a finite driving force. As the exit and inlet temperatures on the two sides of the exchanger approach each other, the size of the heat exchanger also increases. Approach temperatures of around 10 °C are typical.

From a rather broader perspective, we can note that a design study must incorporate aspects of the plant scheduling, particularly if the plant is a typical multiproduct, multipurpose unit. The operation of the heating, cooling and refrigeration systems can also be shown on the Gantt chart. This allows any bottlenecks and constraints to be identified and provides a basis for optimizing resource use across the whole set of operations.

2.3.4.3 Coupled Heat and Mass Balances

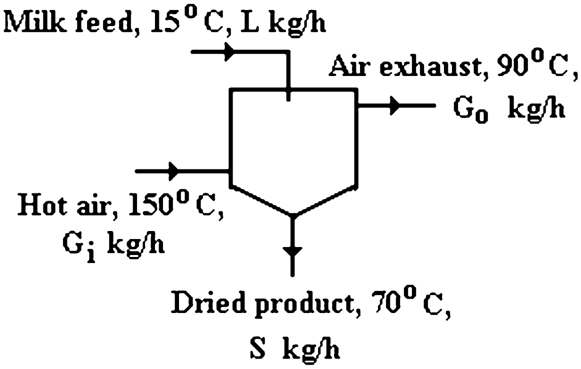
Sometimes it is not possible to solve the mass and energy balances independently. The solution depends on solving both balances simultaneously. This is illustrated in the final example of a spray dryer.

Example 10. 100 kg/h of milk powder containing 2 % moisture are produced in a continuous spray dryer. The feed solution contains 40 wt% milk solids and enters at 15 °C. Atmospheric air with humidity $Y = 0.005$ kg water/kg dry air is heated to 150 °C before entering the dryer. The air stream leaves the dryer at 90 °C, and the solids product leaves at 70 °C. The process is outlined in Fig. 2.23. Neglecting any heat losses, calculate the inlet liquid flow, the air flow, and the exit humidity of the air stream. Set up an overall summary mass and energy balance.

Data:

Mean heat capacity of dry air = 1 kJ/kg K.
Mean heat capacity of water vapor = 1.67 kJ/kg K.
Mean heat capacity of dry solids = 1.6 kJ/kg K.
Mean heat capacity of liquid water = 4.2 kJ/kg K.

Fig. 2.23 Spray dryer



Latent heat of evaporation of water at 0 °C = 2,500 kJ/kg.

Nomenclature:

L = liquid feed rate (kg/h).
g = dry air rate (kg/h).
G_i = total air flow in (kg/h).
G_o = total air flow out (kg/h).
S = product rate = 100 kg/h.

Solution:

Basis: 100 kg spray dried product.
Datum: 0 °C; liquid water.

1. *Balance on dry solids*
   Solids in = Solids out.
   $0.4L = 98$.
   Therefore, $L = 245$ kg/h.
   Water in feed = $0.6L = 147$ kg/h.
2. *Dry air*
   The dry air in (=g) is the same as the dry air out in the wet stream.
3. *Water balance*
   Water in hot air + Water in the liquid feed = Water out in exit air + Water in dried solids

   $$0.005\,\mathrm{g} + 147 = Yg + 2,$$

   where, Y = humidity of exit stream. Thus,

   $$g(Y - 0.005) = 145. \tag{2.49}$$

4. *Enthalpy balance*
   The energy balance is

   $$\text{Enthalpy of } L + \text{Enthalpy of } G_i = \text{Enthalpy of } G_o + \text{Enthalpy of } S, \tag{2.50}$$

   where the enthalpies are respectively:

   L: (147 × 4.2 + 98 × 1.6) × 15 = 11,613 kJ.

Table 2.7 Summary of overall mass and energy balances for Example 10

	In		Out	
Component	kg/h	kW	kg/h	kW
Milk solids	98	0.653	98	3.049
Water	147	2.572	2	0.163
Total (liquid streams)	245	3.225	100	3.212
Dry air	6,351.16	264.63	6,351.16	158.78
Moisture	31.76	24.27	176.75	130.12
Total (air streams)	6,382.92	288.9	6,527.91	288.9
Total	6,627.92	292.13	6,627.91	292.11

G_i: 150 g + 0.005 × g (1.67 × 150 + 2,500) = 163.75 g kJ.
G_o: 90 g + gH(1.67 × 90 + 2,500) = (90 + 2,650.3H) g kJ.
S: (98 × 1.6 + 2 × 4.2) × 70 = 11,564 kJ.

Thus:

$$11,613 + 163.75\,\mathrm{g} = 11,564 + (90 + 2,650.3Y)g$$

or,

$$g(2,650.3Y - 73.75) = 49. \tag{2.51}$$

5. *Solution for g and Y*
   Equations (2.49) and (2.51) can now be solved simultaneously for g and Y, to give:

$$g = 6,351.2\,\mathrm{kg\ dry\ air/h},$$

$$Y = 0.028\,\mathrm{kg/kg\ dry\ air},$$

so that

$$G_\mathrm{i} = 6,351.16 \times (1 + 0.005) = 6,382.9\,\mathrm{kg/h}.$$

$$G_\mathrm{o} = 6,351.16 \times (1 + 0.02783) = 6,527.9\,\mathrm{kg/h}.$$

The heat and mass balance is summarized in Table 2.7. The values in kW are obtained by dividing the enthalpy values above by 3,600.

2.3.5 Energy Integration

The discussion of pasteurization processes illustrated that, as well as considering the design of each individual piece of equipment, it is also important to consider the design of the whole system. This can have great significance for the way in which the individual operations interact with each other—and for the way in which the plant is to be controlled and operated. In particular, the rationalization of energy use across the whole plant must be considered, The pasteurization example showed how a simple recycle loop within the processing line can have a profound effect on energy use. Preheating the feed by the same, but hotter, stream, reduced the steam and cooling requirements dramatically. In a real plant there are potentially many hot and cold streams. The question thus arises: how can the hot streams be used to heat the cold streams to their target temperatures whilst minimizing the cost of equipment, steam, cooling water, and refrigerant?

The problem is readily grasped, but not so easily solved; however, considerable progress has been made in developing the theoretical basis (which is essentially the second law of thermodynamics) and computational methods for solving this class of problem. The approach employed is commonly known as Process Integration or Pinch Technology. Although most of the methods now available were originally developed for continuous processes, techniques have also been formulated for intermittent batch and semi-batch processes. Process integration is an important weapon in the designer's armory, and should certainly be used in design, just as upgrading and resource recovery from "waste" streams must be considered very seriously. Kemp (2006) provides a useful introduction to the subject.

2.4 Conclusions

In this chapter, we have outlined some of the issues and the tools for undertaking the preliminary process design of a food-processing facility. The principal design tools for estimating the material and energy flows and requirements—which are fundamental to the whole process—are material and energy balancing. Some of the principles of these methods and their application to food operations have been outlined. It is stressed throughout that an integral part of any design must be to consider how the various parts of the plant are likely to be used—i.e., scheduling. Bottlenecks that might arise from a lack of equipment or constraints on services, such as energy or cooling supplies, must be identified at the design stage. Equipment (including storage) sizing is profoundly influenced by the scheduling strategy. In any event, an over-riding concern must be to design a plant with a view to flexibility, since the rate of innovation of new products is high in the food sector. The importance of linking together aspects of hygiene (especially CIP), HACCP, product quality, and process control at an early stage in the design process has also been stressed.

References

Blanc, D. (2006) "ISO 22000 – From intent to implementation", Management Systems, May–Jun, 7–11.
Green, D.W. and Perry, R.H. (2008) (eds) "Perry's chemical engineers' handbook", 8th edit., McGraw Hill, New York, NY, Section 2.
Kemp, I.C. (2006) "Pinch analysis and process integration", Butterworth-Heinemann, Oxford, UK, 416 pp.
Rahman, M.S. (2009) (ed.) "Food properties handbook", 2nd edit., CRC Press, Boca Raton, FL, 859 pp.
Sahin, S. and Sumnu, S. G. (2006) "Physical properties of foods", Springer, New York, NY, 258 pp.

Chapter 3
Food-Processing Equipment

C. Skjöldebrand

3.1 Introduction

The present-day food industry has its origins in prehistory when the first food processing took place to preserve foods in case of famine or to improve their eating quality. For example, meat was roasted to improve its quality, and grain was ground to obtain flour for baking bread (Fellows 2009). Equipment was developed to facilitate the operations and to reduce the time taken. Water, wind, and animal power were harnessed. At first the equipment used was on a domestic scale, but later on, as society developed, trade establishments such as bakeries and breweries sprang up. These were the forerunners of the present food industry.

A food process is a set of sequential operations that leads to a product. Every step, which, in most cases, corresponds to an individual piece of equipment, has its own influence on the final properties of the processed product. The design of this equipment is based on a knowledge of transport phenomena, which are at the center of food engineering. This is often defined as "the application of engineering principles to food products." One important cornerstone of food engineering is the unit operation. This concept, which was developed in the 1950s and 1960s, forms the background for studies of individual operations such as distillation, cooking, evaporation, and extraction. For each of these unit operations, transport phenomena underlie the basic mechanisms of operation.

This chapter will cover an introduction to food manufacturing (today and a vision for the future). Some principal types of food processing, packaging, and end-of-line equipment will also be described.

3.2 Food-Processing Equipment in a Production Plant

3.2.1 *Today*

The food industry in Europe in the year 2011 is:

- The largest manufacturing sector with production worth close to 956.2 billion euros (accounting for 16 % of the turnover of manufacturing in the 27-member bloc).

C. Skjöldebrand (✉)
Division of Packaging Logistics/Innovation Engineering, Department of Design Sciences,
Lund University, Lund 221 00, Sweden
e-mail: christina.skjoldebrand@plog.lth.se

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_3,

- Direct employment in the food and drink sector in the EU accounts for 4.1 million jobs and many more jobs indirectly—making the industry the leading employer in the manufacturing industry in the European Union. The industry remains highly fragmented with 274,000 companies (99.1 % of which are small or medium sized).
- One that employs wide-ranging production methods, covering both first- as well as second-stage processing.
- A sector displaying relatively stable overall growth of around 2 %, albeit with significant variations between the various branches that make up the food and drink industry.

In Sweden, the food industry:

- Is the fourth largest branch of industry on the basis of production value
- Is the second largest on the basis of turnover
- Is the third largest on the basis of number of employees
- Employs about 500,000 people within food production, distribution, and handling

With these data as a starting point, it would be quite logical to assume that the food industry today is effective, clean, and employs high technology, including the widespread use of computers in production and process control. You might believe that there are highly competitive enterprises keen to incorporate the latest research and development findings into their production methods. You might also believe that the industry has a high turnover; that its employees are highly motivated, well educated, and highly productive; that its manufacturing processes "pump out" products consistently with the required exacting specifications; and, finally, that production skills are held in high regard. It may also be believed that new products with highly desirable characteristics are often developed, that new business concepts encourage company growth, and that new investments are made when needed.

Most of the above attributes are found in the chemical process industry but not in the food industry. What then do you find when you visit a large, modern food factory of today? Frequently, you will see an expensive production unit, manually operated and very inefficient. In many other manufacturing industries you can observe development, innovation, rationalization, and improvement but not in the food industry (Hesselman 2012). Many of the numerous staff engaged in food production are to a large extent uneducated. Brands are taken care of tenderly; sophisticated marketing and distribution skills are employed. However, staff training is rare. Frequently, operatives are not experienced in working with food. Many of them started with summer jobs and stayed on. Their salary is low and their IT and computer experience is minimal. We see an industry that needs staff with a higher level of higher education and knowledge about their functions in the production units.

Moreover, in the case of food, the consumer is reluctant to drop the old-fashioned approach. We prefer the vision of our mothers stirring the contents of a stew to the picture of a hygienic plant with stainless steel equipment that produces safe food! There are few areas around that are so filled with contradiction as food manufacturing. We want a wide range of quality products with a long shelf life that are, at the same time, inexpensive. Ideally, they should be produced from locally sourced, organic ingredients.

Unfortunately this is the same all over the world. Charming handicrafts and art are applied. The old craftsmen that used to manage the production do not exist any longer. We have neither absorbed their knowledge nor employed compensating technology. A lot of food factories are still run like a home kitchen. That, at least, it is the image that is portrayed—homemade is safe, tastes good, and is cheap!

But who is cracking 700,000 eggs an hour? Who bakes 12,000 loaves of bread an hour? Who is making 5,000 tons of hamburgers an hour? At home or in the restaurant kitchen or...?

At the moment, the food industry is exposed to enormous pressure for change. The competition has already increased significantly, deregulation has occurred, and customs barriers have been removed.

A great deal of structural rationalization is in progress, and consumers are less well protected. Over the past 60 years, food manufacturing has been transformed from a handicraft to a process industry. The resulting changes have been particularly intense during the last 8–10 years. As most people are aware, the food industry is under severe scrutiny by the media, which also touches all of us who are consumers. It is bombarded by questions relating to ethics and hygiene. Demands by the consumer are increasing every day. The trends are towards safer, fresher foods, without additives and at a lower price.

Unfortunately, as discussed above, the education level of many food industry employees is low, and they have little interest in higher education. In 1995, a study of the Swedish food industry found that only 30 companies out of 2,300 employed one engineer or scientist having more than 3 years at university (Björk 1997). In total, around 800 engineers or scientists were employed in the food industry, mainly by the large international corporations. In 1994 the number was somewhat higher. The industry is regarded as having a low status, and this is not good for its employees.

There is also an entrenched conservatism within the food industry, which limits its ability to implement modern techniques and production methods employed in other sectors. This is perhaps due to the fact that few young people have an education in food processing or that there are too few opportunities for education at a higher level.

The above issues are as "hot" in the USA as in Europe. In the States, there is low inflation (as in Europe), low consumer prices, and relatively low unemployment. Published data show that both food industry sales and profits have increased. For example, operating margins increased by 0.6 % during the period 1993–1996, profit margins by 0.2 %/year, and net profits by 1.3 % over the same period. However, there are still ongoing pressures to lower costs, increase market share, and provide more competitive salary packages. Moreover, to meet competition from large-scale imports of cheaper food, the industry has been forced to find ways to increase its productivity.

In the home market, it is becoming more and more important to produce a greater variety of products with a high turnover rate in order to meet consumer demands and, at the same time, to reduce the time between ordering and delivery. The trends towards fresher food with no additives continue. The current attention on food safety issues (e.g., dioxin contamination in Belgium and mad cow disease) puts an increased focus on hygiene and traceability. A mistake can mean the difference between life and death.

Automation occurs in some branches of the industry, for example, the dairy sector. Online sensors to control quality and safety are few. Computers and other IT tools that can be used for planning, simulation, and decision support are rare. Here there is a great potential for development. Where automation occurs, it is normally in the storage and packaging parts of the production process.

In general one can say that the equipment in the food industry is of a very high standard. The design is hygienic and the equipment is well suited for the production of small volumes of product, i.e., the processes are very flexible. New innovative equipment and processes are few and far between. However, the industry has a good record of importing techniques from other industries (e.g., microwave and NIR techniques).

3.2.2 Vision for the Future

Let us visit a small town in Europe. The year is 2020. There are both households and industries located in the town. One of the companies is a small enterprise called "Local Foods." It produces fresh bread and ready-to-eat meals based on bread. About 400 different articles are manufactured. Most of the products, filled French rolls, crepe, pies, Quiche Lorraine, and pizza, are distributed to households close to "Local Foods." New products are developed now and then. Customers can order and buy their food via a TV screen in their homes. The products are dispatched to the customer immediately after preparation, within 1–2 h. If a particular request is made regarding the filling, quality, or size of the product, it can be specified via the screen. The order goes directly into the production computer that controls the processes. The raw materials are based on frozen dough and different fillings such as prawns, minced meat, shellfish, rice, cod, clams, champignons and other types of mushrooms, vegetables, chicken meat, and boiled egg. Storage rooms for raw materials are located at one end of the production unit. There are facilities for both cold and frozen storage of fillings and dough.

The plant and the processes are fully automated, and the line is completely flexible and can be tailored to individual products. Equipment for sterilization, blanching, pasteurization, boiling, deep fat frying, and baking are available. New heating techniques (microwaves, NIR, ultra high pressure) are tested and used when appropriate. Minimal processing, i.e., nonthermal processing or minimum heating, is also used. On the production line, a computer is installed to provide decision support for the operators and to control the processes. The computer programs are easy to use, and the graphic interface and hardware are specially designed to be user friendly to the operators. Online sensors measure the quality properties, such as the color of the crust, GI, health properties, texture, and aroma, and aid traceability. The raw materials are characterized using sensors. When the product is finished, the process stops and the product is packed and sent directly to the customer.

The company has developed relationships with different skilled contractors to keep it updated with the latest tools to improve production efficiency. A robot handles the logistics and assembly of the products. The ventilation for the buffer in which the raw materials are stored before use is of the highest quality and is clean room approved. Energy use within the production unit is optimized, and the production is certified according to ISO standards.

3.3 Description of Food Processes and Equipment in Different Sectors of the Industry

The food industry is divided into several sectors depending on what kinds of raw materials are to be processed (grain, vegetables, fish, meat, etc.). In Sweden the food industry is divided into 13 different sectors or branches; in the European Union, it is divided into nine different branches.

In Sweden:

- Slaughterhouses and meat processing
- Dairy products and ice cream
- Processed fruit and vegetables
- Processed fish products
- Oil and fat
- Grain mill products and starch processing
- Bakeries
- Sugar
- Chocolate and confectionery
- Other food products
- Wine and spirit
- Malt beverages
- Mineral and soft drinks

In the EU:

- Processed meat
- Fish products

- Processed fruit and vegetables
- Oils and fat
- Dairy products
- Grain mill products and starch products
- Animal feed
- Other food products
- Beverages

Table 3.1 shows the different process steps/unit operations employed in each sector of the food industry (Claesson and Skjöldebrand 2002). As can be seen in this table, a number of unit operations are used in all types of production, regardless of the process objectives or the raw materials employed. These are raw material handling, mixing, cooling, filling, packaging, storage, and transportation. Unit operations involving heat treatment comprise 75 % of all processes in the food industry.

3.4 Raw Materials

The demand for processed food tends to be seasonal in nature (Brennan 2006), and supplies of many raw materials are subject to variations in both quantity and quality throughout the year. Such variations may be buffered by sales forecasting, but providing regular supplies of raw materials of a seasonal nature, such as fruits and vegetables, presents problems.

Considerable progress is being made in improving the suitability and the supply of raw materials for food processing. The main directions in which such progress is being made are:

1. Selective breeding of varieties specially for processing
2. Growth programming and contract buying of raw materials
3. Improvement in raw material transportation and storage
4. Improvements in mechanization

Any improvement in the suitability of the raw material for its intended purpose, or in the spreading of the season over which it may be harvested, results in improved processing efficiency and plant utilization. The development of varieties for food processing involves consideration of all those attributes of the raw material, which are reflected in the quality of the finished product. The attributes of importance in this respect are color, shape, function, texture, and maturation characteristics. The development of suitable varieties for processing requires close cooperation between breeders, research stations, and processors.

3.5 Mixing and Emulsification

Mixing may be defined as an operation in which a uniform combination of two or more components is effected (Brennan 2006). The degree of uniformity attainable varies widely. With miscible liquids and soluble solids in liquids, very intimate mixing is possible. With immiscible liquids, paste-like materials, and dry powders, the degree of uniformity obtainable is invariably less.

The materials are fed to a mixer and may vary from low-viscosity liquids to highly viscous pastes or dry powders. Mixing equipment is conveniently classified on the basis of the consistency of the materials that it will handle successfully. The most commonly used form of mixers for handling low or moderate viscosity liquids is the impeller agitator. This type of mixer consists of one or more

Table 3.1 Process steps and unit operations employed in different parts of the food industry (from Claesson and Skjöldebrand 2002)

	Branch unit													
Operation	Meat	Dairy, ice cream	Preserved fruit and vegetables	Preserved fish	Oils and fats	Mill starch	Bakery, pasta	Sugar	Chocolate confectionery	Finished food	Wine and spirits	Malt, beer	Soft drinks (including water)	Other foods (spices, coffee, tea, powdered products, sauces)
Raw material storage	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Cleaning raw materials		×						×						×
Sorting	×		×	×	×	×		×		×				×
Raw material classification	×	×	×	×	×	×	×	×						
Mixing	×	×		×			×		×	×	×	×	×	×
Filtration								×			×	×		
Centrifugation		×						×						
Fermentation	×						×				×	×		
Homogenization	×	×		×						×				
Crystallization		×			×			×	×					
Heat treatment														
Preservation														
Sterilization	×	×	×	×						×				
Pasteurization	×	×	×	×						×				
Blanching			×							×				
Radiation			×											×
Conversion														
Conching									×					
Boiling	×									×				
Baking							×							
Frying	×									×				
Smoking	×									×				

Tempering	×		×	×										
Reheating	×									×				
Warm holding	×									×				
Cooling	×	×	×	×	×		×	×	×	×	×	×	×	
Water activity														
Drying	×	×	×	×		×	×	×	×				×	
Concentration		×												
Phase change														
Freezing	×	×	×	×				×		×				
Thawing (defrosting)	×		×	×						×				
Extrusion		×				×			×	×				
Mounting							×			×				
Filling	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Packaging	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Storage	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Transport	×	×	×	×	×	×	×	×	×	×	×	×	×	×

impellers fixed to a rotating shaft, which create currents within the liquid. These currents should travel throughout the mixing vessel. It is not sufficient simply to circulate the liquid; turbulent conditions must be created within the moving stream. When this comes into contact with a stationary or slow-moving liquid stream, shear occurs at the interface and low velocity liquid is entrained in the faster moving streams. In order to achieve mixing within a reasonable time, the volumetric flow rate must be such that the entire volume of the mixing vessel is swept out in a reasonable time.

A new exciting mixer has been developed by a Swedish company, QB Food Tech AB. It consists of a cubic tank mounted on one of its corners and rotated about a vertical axis. The company claims that the unique flow pattern created within the device makes it capable of mixing powders and liquids faster, to a better quality, and with a lower energy consumption than conventional mixers (QB Food Tech 2012). It can handle batches of 30–4,000 l and continuous in-line mixing up to 50,000 l/h.

When mixing particulate solids, the probability of obtaining an orderly arrangement of particles is virtually zero (Brennan 2006). In practical systems the best mix attainable is that in which there is a random distribution of the ingredients. However, the degree of mixing necessary in any mixing operation depends on the use to which the mixture is to be put and the method of control that is applied. Solids mixing is generally regarded as arising from one or more of three basic mechanisms. These are convection, i.e., transfer of masses or groups of particles from one location to another; diffusion, i.e., the transfer of individual particles from one location to another arising from the distribution of particles over a freshly developed surface; and shear, i.e., the setting up of slipping planes within the mass. Most mixing devices employ all three mechanisms.

Examples of mixers for particulates are tumble mixers, horizontal trough mixers, vertical screw mixers, and fluidized bed mixers. Texts devoted to mixing operations include Harnby et al. (2000), Paul et al. (2004), and Cullen (2009); the latter is specific to foodstuffs.

3.6 Filtration

Solid–liquid filtration, hereinafter termed filtration, may be defined as that unit operation in which the insoluble solid component of a solid–liquid suspension is separated from the liquid component by passing the latter through a porous membrane or septum, which retains the solid particles on its upstream surface or within its structure or both (Brennan 2006). When a suspension of particles is passed through a filter, the solids initially become trapped in the filter medium and, as a result, reduce the area through which liquid can flow. This increases the resistance to fluid flow, and a higher pressure difference is therefore necessary to maintain the flow rate of filtrate (Fellows 2009).

There are different kinds of filtration equipment on the market. Some of them will be briefly mentioned here (Brennan 2006; Sutherland 2008). Filtration equipment can be divided into two types—pressure filters and vacuum filters. In pressure filters, a pressure exceeding atmospheric is maintained upstream of the medium to induce the flow of filtrate through the system. This upstream pressure is achieved by pumping the feed slurry into the filter. Pressure filters may operate at constant pressure throughout filtration or the pressure may gradually increase so as to maintain a constant flow rate of filtrate. Various combinations of these two basic methods may also be used.

In vacuum filters, a subatmospheric pressure is maintained downstream of the medium and atmospheric pressure upstream. Because the pressure drop across the filter is limited to one atmosphere, they are not suited to batch operation. Some types of leaf filter, tube filters, and edge filters are operated batchwise, but continuous vacuum filters are far more common.

3.7 Centrifugation

Centrifugation may be defined as a unit operation involving the separation of materials by application of centrifugal force, which is generated when materials are rotated. The magnitude of the force depends on the radius, the speed of rotation, and the mass (or density) of the centrifuged material. In the separation of immiscible liquids, the denser liquid moves to the bowl wall and the lighter liquid is displaced to an inner annulus. The density of the liquids, the thickness of the layers, and the speed of rotation determine the pressure differences across the layers.

Centrifuges are classified into three different groups (Table 3.2) for:

1. Separation of immiscible liquids
2. Clarification of liquids by removal of small amounts of solids (centrifugal clarifier)
3. Removal of solids (desludging and dewatering centrifuges)

3.7.1 Liquid–Liquid Centrifuges

The simplest type of equipment is the tubular bowl centrifuge. It consists of a vertical cylinder or a bowl, typically 0.1 m in diameter and 0.75 m long, which rotates inside a stationary casing at between 15,000 and 50,000 rpm depending on the diameter. Feed liquid (e.g., animal and vegetable oils and syrup) is introduced continuously at the base of the bowl wall. The two liquids are discharged separately through a circular weir system into stationary outlets (Fig. 3.1).

3.7.2 Centrifugal Clarifiers

The simplest solid–liquid centrifuge is a solid bowl clarifier. This consists of a rotating cylindrical bowl 0.6–1.0 m in diameter. Liquor with a maximum of 3 % w/w solids is fed into the bowl, and the solids form a cake on the bowl wall. When this has reached a predetermined thickness, the bowl is drained and the cake is removed automatically through an opening in its base.

Feeds that contain a higher solids content are separated using nozzle centrifuges or valve discharge centrifuges (Fig. 3.2).

Table 3.2 Applications of centrifuges in food processing (adapted from Fellows 2009)

Centrifuge type	Range of particle sizes (μm)	Solids content of feed (% wb)	Application A	B	C	D	E	F	G	H
Disc bowl										
Clarifier	0.5–500	<5	×	×	×					
Self-cleaning	0.5–500	2–10	×	×	×	×	×			×
Nozzle bowl	0.5–500	5–25	×	×	×	×	×		×	
Decanter	5–50,000	3–60	×	×	×	×	×	×	×	
Basket	7.5–10,000	5–60					×	×		
Reciprocating conveyor	100–80,000	20–75					×	×		

A liquid–liquid extraction, *B* separation of liquid mixtures, *C* clarification of liquids, *D* concentration of slurries, *E* liquid–solid–liquid extraction, *F* dehydration of amorphous substances, *G* dewatering of crystalline substances, *H* wet classification

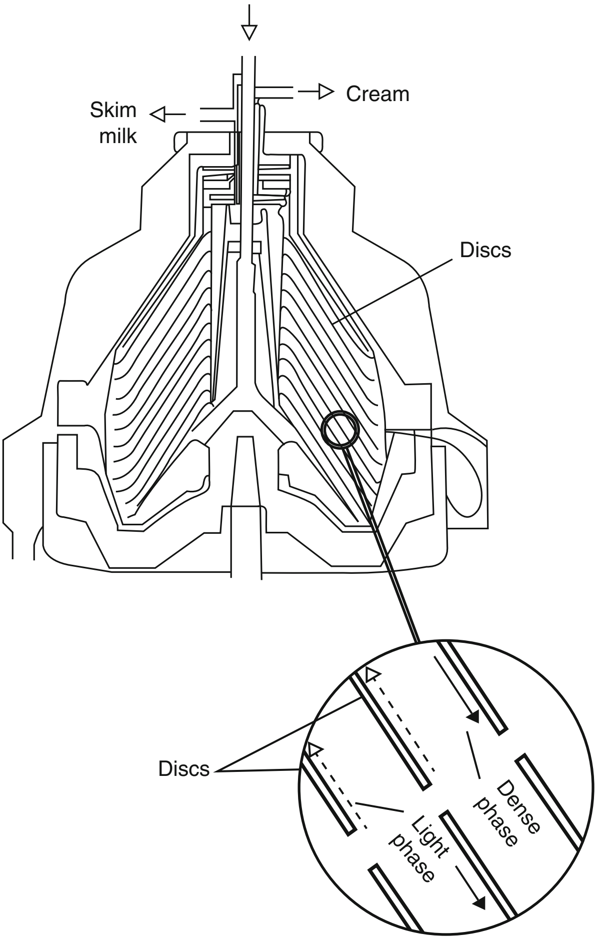


Fig. 3.1 Tubular bowl centrifuge (after Fellows 2009, reproduced with permission from Woodhead Publishing Limited)

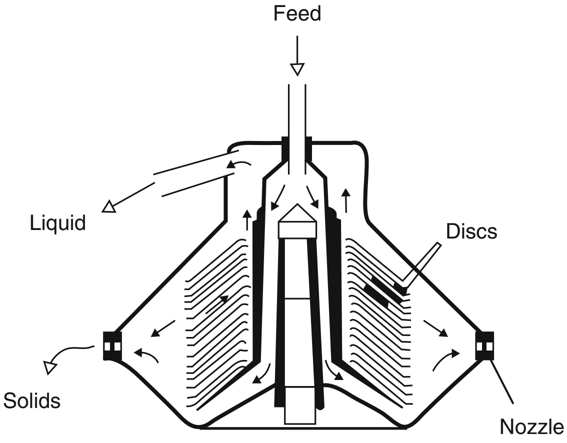


Fig. 3.2 Nozzle centrifuge (after Fellows 2009)

3.7.3 Desludging, Decanting, and Dewatering Centrifuges

Feeds with high solid contents (Table 3.2) are separated using desludging centrifuges (Fellows 2009). A number of designs are available including conveyor bowl, screen conveyor, basket, and reciprocating conveyor centrifuges. In the *conveyor bowl centrifuge*, the solid bowl rotates at up to 25 rpm faster than the screw conveyor. This causes the solids to be conveyed to one end of the centrifuge whereas the liquid fraction moves to the other, larger diameter, end. The solids removed from this equipment are relatively dry compared with other types of equipment. The *screen conveyor centrifuge* is of a similar design, but the bowl is perforated to remove the liquid fraction. This type may have the bowl and screw assembly mounted vertically with liquor fed from the top of the casing.

The *reciprocating conveyor centrifuge* is used to separate fragile solids. Problems caused by buckling of the cake are overcome in a modification of this design called the *multistage reciprocating conveyor centrifuge*. This equipment has a series of concentric reciprocating baskets. The *basket centrifuge* has a perforated metal basket lined with a filtering medium, which rotates at up to 2,000 rpm.

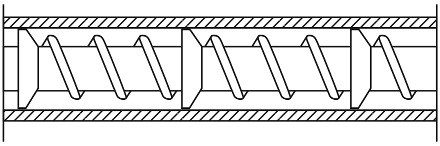
3.8 Extrusion Cooking

Extrusion cooking is a relatively recent form of food processing. Extrusion involves forcing material through a hole (Camire 2002). Sausage extruders were developed in the nineteenth century as simple forming machines. Eventually pasta was produced in extruders. Flour and water were added at one end of the machine, and a screw mixed and compressed the dough before extruding it through numerous holes or dies that gave the pasta its shape. During the 1930s, equipment was developed in which heat was added to the barrel containing the screw; puffed corn curl and other snacks resulted. The pressure developed as the dough moved along the screw; this, together with the heating under pressure, caused the corn to puff as it exited the dies. Specialized extrusion cookers were developed to process more types of food.

The feasibility of cooker extruders, as a form of heat-transfer equipment, has not yet been thoroughly investigated. Knowledge is often lacking on flow phenomena and mixing characteristics in combination with physical properties (viscosity, thermal conductivity) of the food product and how these change during processing (Hallström et al. 1988). Two types of extruders are considered here, the twin-screw extruder and the single-screw extruder (Fig. 3.3). Some general data are given in Table 3.3. There are variants of the single-screw extruder, which can be classified as high-shear cooking extruders.

Considering only the mechanical action of these two types of extruder, the major difference between them lies in how the products flow through them. The single-screw extruder can, in this respect, be characterized as a friction pump, as it is the viscous forces between the barrel and the product, with the aid of the rotation flights that transport the product. The twin-screw extruder, on the other hand, is characterized as a displacement pump in which the “closed” C-shape chambers, formed by the intermeshing screw channels, transport the product.

For further details on the use of extruders in the food industry, see Riaz (2000).



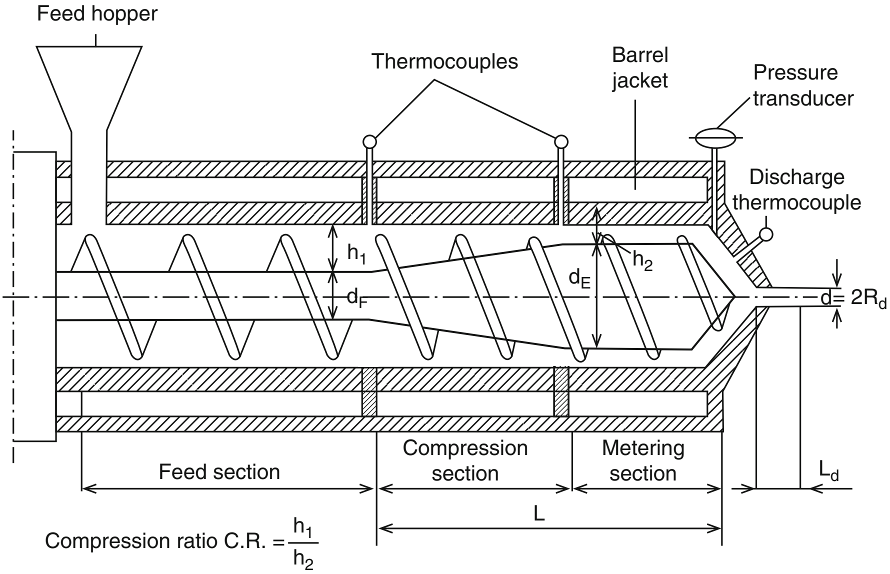


Fig. 3.3 Schematic diagram of a screw extruder (after Hallström et al. 1988)

Table 3.3 Typical data for twin- and single-screw cooker extruders

	Type of extruder		
		Single screw	
Characteristic	Twin-screw low-shear cooker extruded	Collet extruder	High-shear cooker extruder
Feed moisture (%)	28	11	15
Product moisture (%)	25	2	5
Product temperature (°C)	150	200	150
Ratio of screw diameter to flight height	7–15	9	7
No. of parallel screw channels	1	2–4	1–3
Screw speed (rpm)	60	300	450
Mechanical energy input (MJ/kg)	0.4	0.8	1.3
Energy dissipated as product heat (MJ/kg)	0.1	0.4	0.4
Heat transfer from barrel jacket (MJ/kg)	0.2	0	−0.1
Total heat transfer to product (MJ/kg)	0.3	0.4	0.3
Shear rate (s^{-1})	22–47	140	165

3.9 Heat Processing

By far the most important group of processes is those associated with heat processing. An increase or decrease in temperature is employed in 75 % of all process steps in food production. There are a great number of ways of performing such treatments, resulting in a wide variation in equipment for this purpose.

These may be based on convection, conduction, infrared radiation, microwave radiation, electrical resistance, and friction. In conventional practical processes, only convection and conduction are responsible for the equilibration of temperature gradients once they are created by internal heat generation or external heat supply.

Heat treatment processes and equipment are described below. The aims of such processes are summarized in Table 3.4.

3.9.1 Thermal Preservation Processes

There are three main methods of preserving food by heating. These are blanching, pasteurization, and sterilization. Holdsworth (1997) describes both thermal and nonthermal preservation methods.

3.9.1.1 Sterilization and Pasteurization

Heat sterilization is the unit operation in which foods are heated at a sufficiently high temperature and for a sufficiently long time to destroy microbiological and enzyme activity. Heat sterilization of food in containers is an old technology largely attributed to the work of Nicolas Appert in the 1800s. From Appert's work, a substantial industry has developed. For example, the estimated sales of canned products in Europe are around 26,000 million/year (Richardson 2000). Sterilized foods have a shelf life in excess of 6 months. The severe heat treatment during in-container sterilization produces substantial changes in nutritional and sensory qualities of foods. Developments in processing technology therefore aim to reduce the damage to nutrients and sensory components, by either reducing the time of processing in containers or processing food before packaging (aseptic processing).

Pasteurization is a relatively mild heat treatment, usually performed below 100 °C, which is used to extend the shelf life of foods to several days (e.g., milk) or to several months (e.g., bottled fruits)—Fellows (2009). It preserves foods by inactivation of enzymes and destruction of relatively heat-sensitive microorganisms (e.g., non-sporing bacteria, yeasts, and molds) but causes minimal changes in the sensory characteristics or nutritive value of a food. The severity of the heat treatment and the resulting extension of the shelf life are determined mainly by the pH of the food. In low-acid foods ($pH > 4.5$), the main purpose is the destruction of pathogenic bacteria, whereas below pH 4.5, the destruction of spoilage microorganisms or enzyme inactivation is usually more important.

When pasteurized or sterilized, the products are either heated in a package or directly heated before being packed. Liquid products are often (but not always) heated before being packaged in a continuous flow process. Solids are normally heat treated after packaging. The equipment used in these processes is described below.

A number of different types of equipment can be used for sterilization and pasteurization of liquid foods before they are packed. These are:

- Tubular heat exchangers
- Plate heat exchangers
- Scraped surface heat exchangers
- Cooker extruders
- Boiling pans and kettles
- Microwave heaters
- Electric resistance heaters

Table 3.4 Heat treatment processes and equipment

Unit operation	Products	Objectives	Wanted changes	Unwanted changes
Preservation processes				
Sterilization	Milk, meat, meat products, fruit, vegetables	Heated to >100 °C	Destruction of sporulated microorganisms	Color, vitamins, nutritional value, quality
Pasteurization	Milk, beer, juice, meat, eggs, bread, convenience foods	Heated to 75–95 °C	Inactivation of sickness bacteria	Color, nutritional value, sensory properties
Blanching	Vegetables	Heated to 90–100 °C using water/steam	Inactivation of enzymes, reduction of oxygen, reduction of bacteria, reduction of raw and bitter taste, change of consistency	Nutritional loss, color, leakage
Conversion processes				
Boiling	Vegetables, meat, fish	Heated to 100 °C using water vapor or water	Inactivation of enzymes, texture, protein changes, starch changes	Nutritional loss, color, leakage
Baking	Bread	Heated to >200 °C	Crust, protein changes, destruction of microorganisms	Nutritional loss, water leakage, mutagens
Oven cooking	Meat, fish	Heated to >200 °C	Crust, protein changes, destruction of microorganisms	Nutritional loss, mutagens, acrylamides, leakage
Frying	Meat, fish	Heated to 150–180 °C	Crust formation, color	Nutritional loss
Tempering processes				
Tempering	Meat	To a temperature about 10 °C	Temperature increase and some phase change	Structure
Reheating	Potatoes, meat and ready-to-eat products	Heating to a temperature >60 °C	Temperature increase to make product suitable for eating	Nutrition, texture, water losses
Warm holding	Potatoes, meat and vegetables	Hold the product at eating temperature (60 °C)	No changes should occur	Nutrition, texture, leakage
Cooling	Meat, fruits, vegetables, fish, potatoes	To a temperature below 10 °C	Temperature drop	Nutrition, texture, water losses, microorganism growth
Water activity				
Drying	Vegetables, meat, potatoes, milk	Remove water at around 100 °C	Reduce weight, reduce microorganisms	Nutrition, chemical changes, structure
Evaporation	Milk, juice	Remove some water at 50 °C	Reduce water	Nutrition, chemical changes
Phase changes				
Freezing	Vegetables, berries, fruit, meat, bread	To a temperature <−18 °C	Water changes to ice, reduce microorganisms, prolonged storage	Structure
Thawing	Vegetables, fruit, meat	To a temperature about 5 °C	Ice changes to water	Structure, nutrition

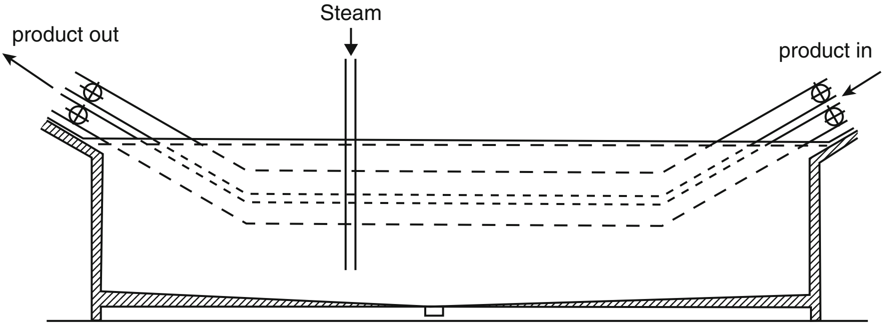


Fig. 3.4 Immersion blancher (after Hallström et al. 1988)

For more details about these techniques, see Fellows (2009), Hallström et al. (1988), and Holdsworth (1997).

The Swedish company Pastair AB has developed a cold process for the pasteurization of liquid foods such as dairy products, fruit juices, and egg white (Pastair 2012). In this process, ozone, which is produced from air in an ozone generator, is injected into the product and maintained in contact with it for a fixed length of time. The product is then heated up to 60 °C for a short period to expel the residual O_2 and O_3. In contrast to thermal processes, minimal changes to the taste and nutritional value occur and enzyme inactivation is minimal. The reduction of microorganisms, however, is comparable to that achieved with conventional pasteurization, i.e., up to 99.9 %.

Retorts using steam for sterilization and pasteurization of food products in cans, bottles, and polyethylene bags may be of the following types:

- Batch retorts, without agitation
- Rotating retorts, without agitation
- Continuous process retorts
- Hydrostatic retorts
- Hydrolock retorts

Again, further details are given by Fellows (2009), Hallström et al. (1988), and Holdsworth (1997).

3.9.1.2 Blanching

Blanching is used to destroy enzyme activity in vegetables and some fruits prior to further processing (Fellows 2009). As such, it is not intended as the sole method of preservation but as a pretreatment, which is normally carried out between the preparation of the raw material and later operations (particularly heat sterilization, dehydration, and freezing). Blanching is also combined with peeling and/or cleaning of food, to achieve savings in energy consumption, space, and equipment costs. The principle types of blancher are described below.

In *water blanchers*, the product is transported through hot water by means of a rotary screw or a rotary drum or on a belt conveyor. One of the simplest designs, an immersion blancher, is illustrated in Fig. 3.4. The water is normally heated by the injection of steam. This design has certain drawbacks. With regard to the heat sensitivity of the product, rapid cooling is important. Furthermore, energy consumption is high. Both of these factors are improved in a design that includes a cooler. Water used in the cooling section is passed through heat exchangers that are used to heat the water for preheating the product. In this way, only a minor part of the heat treatment takes place in hot water heated up by the live steam. The principle is illustrated in Fig. 3.5.

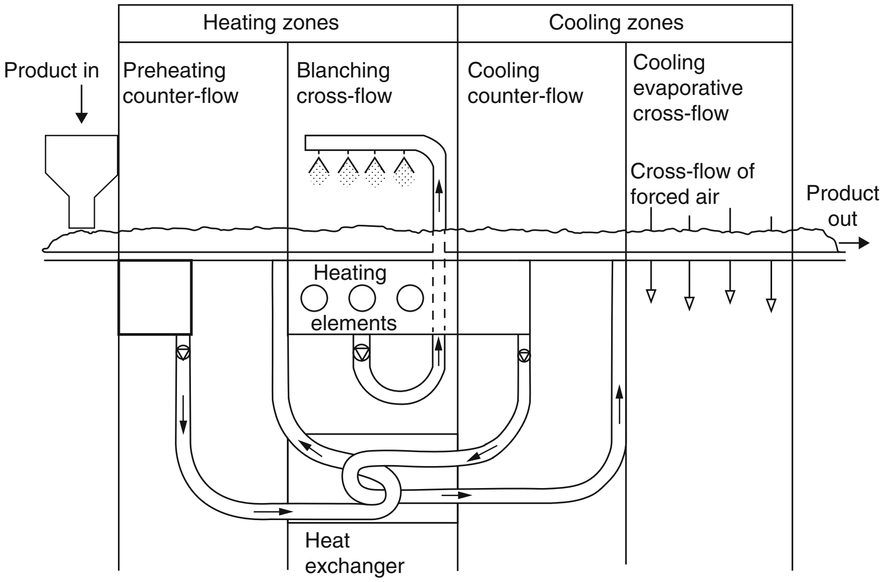


Fig. 3.5 Continuous water blancher using cooling section (after Hallström et al. 1988)

In *steam blanchers*, product transport through the equipment takes place in the same way as in water blanchers. Steam is injected onto the product surface and rapid heating occurs in this environment. Heating time and heat economy may be improved by means of different design features such as reduced thickness of the product, improved steam injectors, rotary valves or seals for minimizing steam losses, and heat recovery systems. In a special design, a vibrating screw transports the vegetables inside the blancher. It is claimed that, in this way, the products move around and heat-transfer efficiency is improved. Spiraling or stacking in the conveyor also results in a much more compact design.

For blanching of large products, the required heating time at the geometric center of the product may be rather long in the equipment described above. Other designs are available; for more information, see Hallström et al. (1988).

3.9.2 Conversion Processes

The manufacture of foods involves two broad types of conversion—those concerned primarily with physical changes and those in which irreversible chemical changes are the main purpose of the activity (Brennan 2006). This part of the chapter deals with processes that aim to change the product chemically. Examples include boiling, baking, frying, and roasting.

3.9.2.1 Boiling

As shown in Table 3.4, boiling means heating of the food at 100 °C using water or steam (Hallström et al. 1988). The aim is to inactivate enzymes and to bring about desirable texture and protein changes.

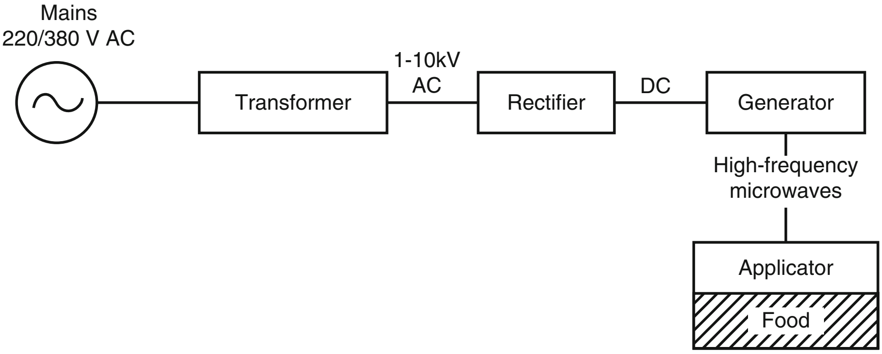


Fig. 3.6 Microwave heating equipment (after Hallström et al. 1988)

3.9.2.2 Baking and Roasting

Baking and roasting are essentially the same unit operation in that they both use heated air to alter the eating quality of foods. The term *baking* is usually applied to flour-based foods or fruits and roasting to meats, nuts, and vegetables. A secondary purpose of baking is preservation by destruction of microorganisms and reduction of the water activity at the surface of the food. However, the shelf life of most baked food is short unless it is extended by refrigeration or packaging (Fellows 2009; Hallström and Skjöldebrand 1983).

Ovens are used in the food industry for the baking of bread and potatoes and for roasting meat (Hallström et al. 1988). They are also used for reheating ready-made frozen and chilled meals. In very few cases they may also be used for boiling; in such cases steam is generated in the oven. The oven consists of either a compartment with one or several shelves for the product or a long tunnel through which the product is transported on a conveyor belt. In the oven, the heat-transfer medium is usually air, which is sometimes mixed with steam. The air may be circulated using a fan. Consequently, the heat-transfer mechanism is either natural or forced convection. To some extent, heat is also transferred via radiation from the walls and via conduction from the shelves.

Forced convection tunnel ovens (Hallström et al. 1988) are very similar to natural convection ovens but have a fan, which may be placed, in different positions. The oven may be divided into a number of sections with one fan in each or have a single fan, which accommodates the whole oven.

Microwave and near-infrared ovens (NIR) are also used to a limited extent on the industrial scale. Equipment for microwave heating consists of a microwave generator (magnetron), which operates at either 2,450 or 915 MHz, a transformer, a reflector, a rectifier, and a device for controlling the supply of microwave energy to the food (see Fig. 3.6). The magnetron needs a direct current of a few kilovolts to operate. At 2,450 MHz, magnetrons are available at output power levels ranging from 400 to 5,000 W. Industrial equipment is mostly based on 2,500 kW modules. The efficiency is between 50 and 65 %, calculated from the supplied electric power. At 915 MHz, only high-power 25–450 kW magnetrons are available. Their efficiency is about 75 %. The microwave power is transferred from the magnetrons to the food by means of an applicator. Many different designs of applicators are available from purpose-built cavities to designs for special applications.

The basic characteristics of near-infrared radiation are high heat-transfer capacity, heat penetration directly into the product, and a fast regulated response (Ginzburg 1969; Skjöldebrand 2000, 2002). These qualities indicate that infrared radiation should be an ideal source of energy for heating purposes. In contrast to microwave heating, the penetration characteristics are such that a suitable balance between surface and body heating can be reached, which is necessary for an optimal processing result. The work of Ginzburg (1969) may serve as a background for heat penetration calculations.

3.9.2.3 Frying

The simplest and most common type of equipment for industrial frying is the frying table. Equipment for continuous griddling or shallow frying of hamburgers, meatballs, steaks, fish fillets, and sausages has been developed from frying tables. Straight in-line systems of this type also exist, with transport rods or moving pans. Continuous systems utilizing Teflon belts as the frying surface with overhead electrical heating elements have been developed in order to avoid burning and to reduce the fat absorption.

In deep fat frying, heat is transferred via convection from oil to the product. The heat-transfer coefficient has been found to vary during the process. This will govern the rate that heat is transferred to the product. Water from the product is evaporated causing turbulence in the fat, resulting in an increased heat-transfer rate (Hallström et al. 1988).

During recent years contact frying of foods has gained increasing interest for industrial purposes as an alternative to deep fat frying. In the case of single-sided contact frying, the product has to be turned over during the process in order to treat both sides. With double-sided contact frying, the necessary frying time can be reduced to less than 50 % compared with single-sided frying for a product of normal thickness. Obviously only flat products like hamburgers, cutlets, bacon, meat cubes, breaded products, and potato products can be fried using this technique. A continuous double-sided Teflon belt grill has been investigated by Dagerskog and Bengtsson (1974) who studied the relationship between crust formation, yield, composition, and processing conditions.

3.9.3 Processes Effecting a Temperature Change

3.9.3.1 Tempering

Tempering is often used to raise the temperature of frozen products, especially meat, to a value at which it is not yet defrosted but is easy to cut into pieces or easy to handle.

Electromagnetic radiation in three different frequency regions is used for tempering purposes. Very low frequencies (<50 Hz) are used to temper blocks of fish (Jason 1974). At such low frequencies, the impedance of fish (or meat) is almost entirely resistive, and the procedure is sometimes called "resistive heating" (Hallström et al. 1988).

When frequencies in the range 300 kHz to 300 MHz are used, the method is called "dielectric heating." Here the product is immersed in either water or air as it passes on a conveyor belt between two parallel-plate electrodes. This can be compared to microwave heating (300 MHz to 300 GHz) where the material is passed through a multimode cavity, which is coupled to a magnetron by a waveguide.

3.9.3.2 Cooling/Chilling

Cooling or chilling is the unit operation in which the temperature of a food is reduced to between -1 and 8 °C. It is used to reduce the rate of biochemical and microbiological changes and to extend the shelf life of fresh and processed foods. It causes minimal changes to the sensory characteristics and nutritional properties of foods, and as a result, chilled foods are perceived by the consumer as being "healthy" and "fresh." Chilling is often used in combination with other unit operations (e.g., fermentation, irradiation, or pasteurization) to extend the shelf life of mildly processed foods.

3.9.4 *Processes Involving Phase Transitions*

3.9.4.1 Freezing

Freezing is a commonly employed means of preserving food products (Skjöldebrand 1990). Most of the water within the food changes to ice. The phase change of the water molecules occurs gradually depending on the degree of binding within the food structure. An American, Clarence Birdseye, founded the modern frozen food industry in 1925. As a fur trader in Labrador, Birdseye had noticed that fillets of fish left by the natives to freeze rapidly in arctic winters retained the taste and texture attributes of fresh fish better than fillets frozen in milder temperatures.

Depending on the cooling medium used, the available equipment for freezing may be grouped as follows:

- Convective (air) freezers
- Conductive (plate) freezers
- Liquid nitrogen and Freon freezers

Convective (air) freezers: Traditionally, convective (air) freezers have been used to freeze food products. In the original and simplest type, the foodstuff is placed in a cold store and surface heat transfer occurs through natural convection. This method is still commonly employed today, especially in small food factories. However, it suffers from the deficiency that the rate of freezing is slow, which on occasion may be detrimental to product quality. Moreover, other products in the store may deteriorate as a result of temperature fluctuations as the doors are opened and closed and as fresh unfrozen product is added.

In blast freezing, cooled air is forced over the product (Hallström et al. 1988). The velocity of the air is of importance as it determines the net heat-transfer coefficient. In air freezing, the low temperature is generally effected by means of a heat pump. However, to some extent, liquid nitrogen is also used.

Conduction freezers: Conduction freezers (also called plate freezers) were developed to improve heat transfer for regularly shaped solid food. The foodstuff is pressed between metallic plates containing channels in which the refrigerant is circulated. The design may vary in the degree of sophistication. A special design for freezing liquid food into pellets is also available. The liquid is poured into small cavities in a rotating drum cooled from the inside.

Cryogenic (nitrogen and Freon) freezers: The original direct-fluid freezers employed some form of brine in which the foodstuff was immersed. For a variety of reasons, mainly hygiene, this method is seldom used today. Rather, liquid nitrogen (LN_2) is often used either for immersion of the product or for spraying on to the product. Due to its low boiling point ($-196\ ^\circ C$) and the highly effective contact between the liquid and the foodstuff, freezing is very fast. As a result, cryogenic freezers are well suited to freezing products having a low solid content (e.g., soft fruits and seafood).

3.9.4.2 Thawing

During thawing, energy has to be transferred into the product in order to both raise its temperature and to melt the ice. This energy may be transferred in different ways. The most common methods are by means of air, water, or microwaves. Other methods such as vacuum and infrared radiation may also be used. The thawing method chosen depends on the thermal properties of the foodstuff, the rate of heat convection from the product, or the dielectric or resistive properties. The thermal conductivity is 2–3 times lower in a thawed product than in a frozen one due to differences in the properties of water and ice.

Table 3.5 Principal differences between thawing in air and thawing in water

	In water	In air
Advantages	– High heat-transfer coefficients – Low flow rate adequate – Uniform heating of product surfaces – Batch and continuous flow operation possible – Low labor cost	– Low capital cost for batch operation – Versatile—can be used for dry products – Batch and continuous flow operation possible – Little mechanical maintenance possible
Disadvantages	– Leaching of flavor components – Water logging with some products – Bacterial contamination a possible hazard – Recirculation and careful filtration necessary to conserve water demand – Corrosion difficult to prevent – Continuous flow operation employs expensive mechanism requiring much maintenance – Cleaning difficult – Cannot be used for dry products	– Large flow rate and high turbulence necessary – Risk of oxidizing some fatty products – Risk of drying moist products – Bacterial hazards with some products – Cleaning difficult – Odor problems – Uniform heating difficult – Continuous flow operation expensive

Nearly all problems encountered in thawing arise from carrying out the process too rapidly. These are connected with:

- The rate of convective heat transfer to the product surface
- The rate of thermal conduction
- The rate of thermal damage

A variety of equipment is used for thawing. The most common methods are convective thawing in which heat is transferred from air or water, vacuum thawing, and dielectric thawing. These methods are described briefly below.

Table 3.5 shows the principal differences between thawing in air and thawing in water. At present, air blast thawing is the most widely used method, largely as a result of its low capital costs. Even though it is a relatively slow method, it may be used for all kind of products. Convective heat transfer in an air thawer is accomplished either by condensation of water on the cold surface or by evaporation. In practice, condensation from a nearly saturated atmosphere can contribute considerably to the fraction of total enthalpy change required for thawing. The relative humidity has to be high in order to prevent the surface from drying out. Control of relative humidity is unnecessary for packaged materials, but it should be maintained between 85 and 95 % for unwrapped products. In an air thawer, the surface heat-transfer coefficient is in the range 10–60 W/m^2 K.

Vacuum thawing is inevitably a batch process, and the capacity of commercially available equipment is seldom greater than 2 tons. However, this poses no problem for relatively thin materials (<5 mm thick) as very rapid rates of thawing can be attained, and this enables the unit to perform a large number of operating cycles in a working day. The APV Torry Vacuum Thawer is one example of this type of process. Figure 3.7 shows the principle of the method. The equipment consists of a large number of vacuum vessels containing the product, which is supported on the open mesh trays stacked on trolleys.

Dielectric (radio frequency and microwave) thawing, which employs similar technology to dielectric tempering, is the most rapid and most versatile method of thawing. The required energy is produced as a result of dielectric losses when a product is subjected to an alternating electric field. Apart from its rapidity, dielectric heating offers the following advantages:

- Uniform heating to a temperature, which need not exceed a few degrees above 0 °C.
- Continuous conveyor operation.

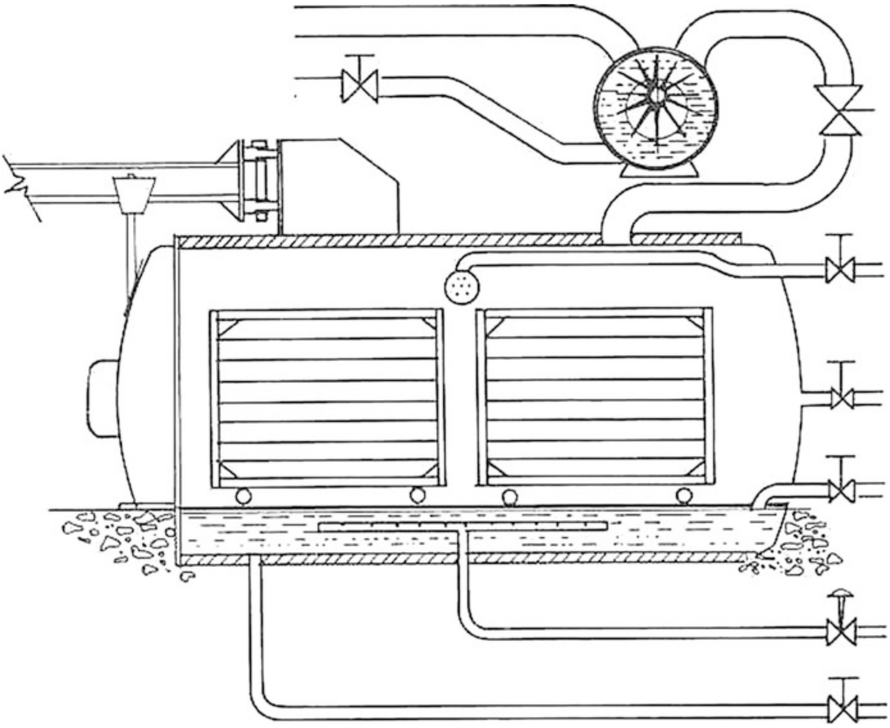


Fig. 3.7 Vacuum thawing equipment (after Hallström et al. 1988)

- Minimum drip loss and no evaporation loss.
- High level of hygiene.
- Thawing can take place within the package.
- No need to be in contact with the product.
- Negligible water consumption.
- Versatility.

There are, however, disadvantages associated with this method. For example, the dielectric properties of the food are dependent on the temperature, especially between −10 and 0 °C, and there is a substantial risk of local overheating. Microwave thawing may only be used for 30–60 mm thick products.

3.9.5 Removal of Water

3.9.5.1 Evaporation

Evaporation—the concentration of a solution by boiling off a solvent (normally water)—has three major applications in the food industry:

1. To pre-concentrate a liquid prior to further processing, e.g., before spray drying, drum drying crystallization
2. To reduce liquid volume in order to cut storage, packaging, and transportation costs

3. To increase the concentration of soluble solids in food materials as an aid to preservation, e.g., as in sweetened condensed milk manufacture

Industrial evaporator systems normally consist of:

- A heat exchanger to supply sensible heat and latent heat of evaporation to the feed. In the food industry, saturated steam is usually used as the heating medium.
- A separator in which the vapor is separated from the concentrated liquid phase.
- A condenser to effect condensation of the vapor and its removal from the system. This may be omitted if the system is working at atmospheric pressure.

Climbing-film and falling-film evaporators in which the residence time of the feedstock is only of the order of a few seconds are widely used for processing heat-sensitive products such as fruit juices and milk. Other types have been described by Ranken et al. (1997).

3.9.5.2 Dehydration

The object of drying (dehydration) is to remove water, most often by means of heating, to increase the keeping quality of the food, and to bring down the cost of storage and transportation (Skjöldebrand 1990). The water content is linked to another entity called water activity, which describes the availability of water for biological reactions and microbiological growth.

Modern drying equipment is based on technologies that come from traditional methods that have been used for hundreds of years. Methods based on convection have their origins in sun and wind drying. However, today the air velocity is controlled as well as the temperature and humidity. Conduction drying used to be carried out in vessels. Nowadays, this is undertaken by controlling temperature as well as pressure, e.g., in vacuum dryers.

Dryers are available in a wide variety of designs and sizes for both batch and continuous operation. For further details, see Baker (1997). Broadly speaking, dryers may be classified as convective, contact (conductively heated), and special types. Some of the more commonly used varieties are described below.

Bin (deep-bed) dryers: Bin dryers are cylindrical or rectangular containers fitted with a mesh base. Hot air passes up through a bed of food at relatively low speed. These dryers have a high capacity and low capital and running costs. They are mainly used for finishing (to 3–6 % moisture content) after initial drying in other types of equipment.

Cabinet (tray) dryers: These consist of an insulated cabinet fitted with shallow mesh or perforated trays, each of which contains a thin (2–6 cm deep) layer of food. Hot air is circulated through the cabinet at 0.5–5 m/s. A system of ducts and baffles is used to direct air over or through each tray to promote uniform air distribution.

Conveyor (belt or band) dryers: Continuous conveyor dryers are sized up to 20 m long and 3 m wide. Food is dried on a mesh belt in beds 5–15 cm deep. The airflow is initially directed upwards through the bed of food and then downward in later stages to prevent dried food from blowing out of the bed (Fellows 2009).

Fluidized bed dryers: These consist of vessels of rectangular or circular cross section with mesh or perforated bases that contain a bed of particulate foods up to 15 cm deep. Hot air is blown through the bed (Fig. 3.8) causing the food to become suspended and vigorously agitated (fluidized). The air thus acts as both the drying and the fluidizing medium. Conventional fluidized bed dryers are limited to small particulate foods that are capable of being fluidized without excessive mechanical damage (e.g., peas, diced or sliced vegetables, grains, powders, or extruded foods). However, vibrated types may be used to dry larger or difficult-to-fluidize particles.

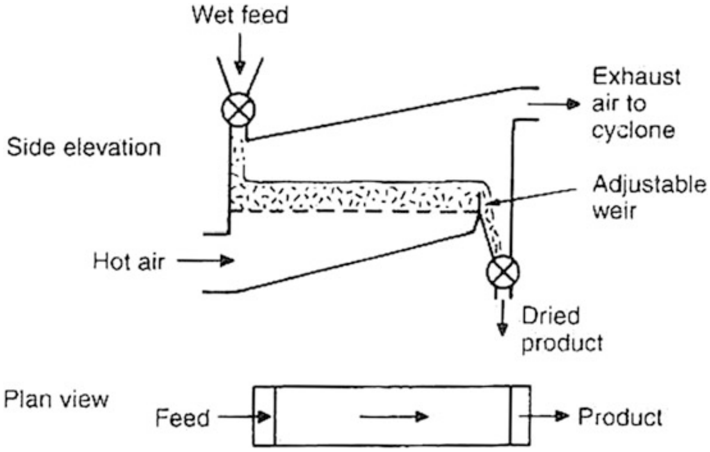


Fig. 3.8 Fluidized bed dryer (after Baker 1997)

Kiln dryers: These are two-storey buildings in which a drying room with a slatted floor is located above a furnace. Hot air and products of combustion from the furnace pass through a bed of food up to 20 cm deep. These dryers are used traditionally for drying apple rings, hops, and malt.

Pneumatic (flash) dryers: In pneumatic dryers, powders or particulate foods are continuously dried in a vertical or horizontal metal duct. A cyclone separator is used to remove the dried product. The moist food (usually less than 40 % moisture) is metered into the ducting and suspended in hot air. Pneumatic dryers are often used after spray dryers to produce food, which has a lower moisture content than normal.

Rotary dryers: A slightly inclined rotating metal cylinder is fitted internally with flights to cause the food to cascade through a stream of hot air as it moves through the dryer. Airflow may be parallel or countercurrent. The agitation of the food and the large area of food exposed to the air produce high drying rates and a uniformly dried product. Rotary dryers are used for the drying of, for example, sugar crystals and cocoa beans.

Spray dryers: The pre-concentrated liquid foodstuff is first “atomized” to form droplets (10–200 µm in diameter) and sprayed into a current of heated air at 150–300 °C in a large drying chamber. The feed rate is controlled to produce an outlet air temperature of 90–100 °C, which corresponds to a wet-bulb temperature (and product temperature) of 40–50 °C. Complete and uniform atomization is necessary for successful drying. Spray dryers are widely used, for example, in the drying of milk. Masters (1985, 2002) provides extensive and detailed descriptions of the technology.

Trough (belt-trough) dryers: Small uniform pieces of food (e.g., peas or diced vegetables) are dried on a mesh conveyor belt, which hangs freely between rollers, to form the shape of a trough. Hot air is blown through the bed of food, and the movement of the conveyor mixes and turns it to bring new surfaces continually into contact with the drying air. These dryers exhibit high drying rates, high efficiency, good control, and minimal heat damage to the product. They are not suitable for sticky foods.

Tunnel dryers: Thin layers of food are dried in trays, which are stacked on trucks programmed to move semicontinuously through an insulated tunnel. Different designs use different airflow configurations (see Fellows 2009).

Sun (solar) drying: Sun drying (without equipment) is the most widely practiced agricultural processing operation in the world; more than 250 million tons of fruits and grains are dried annually

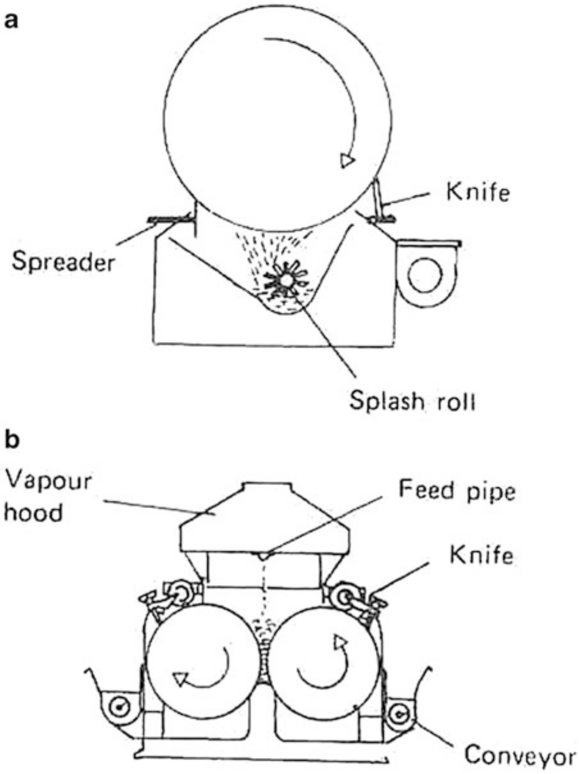


Fig. 3.9 Drum dryers: (**a**) single drum, (**b**) double drum (after Fellows 2009)

using this technique. In some countries, foods are simply laid out on roofs or other flat surfaces and turned regularly until dry. A range of solar drying equipment, which gives improved control and hygiene, is also available. For details, see Imre (1997).

Dryers in which heat is supplied to the food by conduction have two main advantages over hot air drying:

1. It is not necessary to heat large volumes of air before drying commences; the thermal efficiency of contact dryers is therefore higher than that of convective dryers.
2. Drying may be carried out in the absence of oxygen to protect components of foods that are easily oxidized.

Two examples of contact dryers are described below.

Drum dryers: Slowly rotating hollow steel drums are heated internally by pressurized steam to 120–170 °C. A thin layer of food is spread uniformly over the outer surface by dripping, spraying, or spreading, or with the aid of auxiliary feed rollers. Before the drum has completed one revolution (within 20 s to 3 min), the dried food is scraped off the drum by a sharp blade, which is in contact with the surface uniformly along its length. The dryer may feature a single drum, a double drum, or a twin drum (Fig. 3.9). Drum dryers are used to produce potato flake, precooked cereals, molasses, some dried soups, fruit purée, whey, and distillers soluble for animal feed formulations.

Vacuum-band and vacuum-shelf dryers: A food slurry is spread or sprayed onto a steel belt (or band), which passes over two hollow drums within a vacuum chamber at 1–70 Torr. The food is dried first by a steam-heated drum and then by steam-heated coils or radiant heaters located over the band. This technique is used for heat-sensitive food.

Table 3.6 Legislation concerning food irradiation

European Union clearances
Only for dried aromatic herbs, spices and vegetable seasoning; Austria, Bulgaria, Cyprus, Denmark, Estonia, Finland, Greece, Hungary, Ireland, Latvia, Lithuania, Luxemburg, Malta, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden
Dried aromatic herbs, spices and vegetable seasoning and other specified items: Belgium, Czech Republic, France, Germany, Italy, Poland, The Netherlands, and United Kingdom
Non-EU countries in Europe
Clearance: Croatia, Czech Republic, Hungary, Norway, Poland, Russian Federation, Switzerland, Turkey, Ukraine, Former Yugoslavia
Other countries with clearances
Asia/Pacific: Australia, Bangladesh, P.R. China, Republic of China (Taiwan), Indonesia, India, Iran, Japan, Korea, Pakistan, Philippines, Thailand, Vietnam.
Africa (Including Middle East), Egypt, Israel, South Africa, Syria
Latin America (Middle and South): Argentina, Brazil, Chile, Costa Rica, Cuba, Mexico, and Uruguay
North America: Canada, United States of America

3.10 Irradiation

In this process, food is sterilized by ionizing radiation (Ehlermann 2002; Arvanitoyannis 2010). Soon after the discovery of radioactivity and X-radiation, it was noticed that ionizing radiation could induce biological effects. From the multitude of atomic particles known, only gamma rays from nuclear disintegration and accelerated electrons are used for food processing. Electrons may be converted into X-rays by stopping them in a converter or target. Other particles such as neutrons are unsuitable because induced radioactivity is produced. The interaction of ionizing radiation with matter takes place by means of a cascade of secondary electrons carrying enough kinetic energy to cause ionization of atoms and molecules and the formation of free radicals. In addition to these direct effects and primary chemical reactions, chain reactions of secondary and indirect transitions take place. In systems as complex as food and for biological systems that are usually high in water content, most primary reactive species are formed by the radiolysis of water, and the pathways of further reactions largely depend on composition, temperature, dose rate and relative reactivities.

The irradiation process is basically very simple. The goods are brought by a transport system into the irradiation cell, which is essentially a concrete bunker shielding the environment and the workers from radiation. A tunnel system allows free access for the goods but prevents radiation leakage; adequate guarding prevents unintentional access by anything or anyone when the radiation is turned on.

In its standard on food irradiation, the Codex Alimentarius does not restrict the use of irradiation to individual foods or to groups or classes of foods. Most countries have preferred to regulate by this approach. Table 3.6 summarizes the legislation relating to food irradiation.

3.11 Food Storage

Food being stored may become spoiled by three mechanisms:

1. Living organisms (e.g., vermin, insects, fungi, or bacteria) may feed on the food and contaminate it.
2. Biochemical activity within the food itself (e.g., respiration, staling, browning, and rancidity development) may in time diminish its quality and usefulness.

3. Physical processes (e.g., bursting and spoilage of the contents of packages or recrystallization phenomena in sugar confectionery, fats, and frozen products) may have the same effect.

The three main factors of the storage environment, which influence the storage life of a particular commodity, are the temperature, humidity, and composition of the store atmosphere. In addition, rough handling, careless packing, or unsuitable packaging can reduce storage life.

3.12 Packaging

Packaging is an integral part of food processing. It performs two main functions: to advertise foods at the point of sale and to protect foods to a predetermined degree for the expected shelf life (Fellows 2009). The main factors that cause deterioration of food during storage are:

- Mechanical forces (impact, vibration, compression, or abrasion)
- Climatic influences that cause physical or chemical changes (UV light, water vapor, oxygen, temperature changes)
- Contamination (by microorganisms, insects, or soils) and pilferage, tampering, or adulteration

In addition, the packaging should not adversely affect the product, for example, by migration of toxic compounds, by reaction between the pack and the food, or by selection of harmful microorganisms in the packaged food. Other requirements of packaging are smooth efficient and economical operations on the production line, resistance to breakage (e.g., fractures, tears, or dents caused by filling and closing equipment, loading/unloading, or transportation), and minimum total cost.

The main marketing considerations are:

1. The brand image and style of presentation required for the food
2. Flexibility to change the size and design of the containers
3. Compatibility with the method of handling distribution
4. The requirements of the retailer

There are two main groups of packaging materials:

1. Retail containers (or consumer units), which protect and advertize the foods in convenient quantities for retail sale and home storage (e.g., metal cans, glass bottles, jars, rigid, and semirigid plastic tubs; collapsible tubes; paperboard cartons; and flexible plastic bags, sachets, and over wraps)
2. Shipping containers, which contain and protect the contents during transport and distribution (including wooden, metal, or fiberboard cases, crates, barrels, drums, and sacks)

See Campbell (1997) for further details of packaging and other end-of-line equipment.

References

Arvanitoyannis, I.S. (2010) (ed.) “Irradiation of food commodities”, Academic Press, London, 710 pp.
Baker, C.G.J. (1997) (ed.) “Industrial drying of foods”, Blackie Academic & Professional, London, 309 pp.
Björk, G. (1997) “National Swedish Research Programme for Food”, The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning, SOU 1997:167.
Brennan J.G. (2006) (ed.) “Food processing handbook”, Wiley-VCH, Weinheim, Germany, 582 pp.

Camire, M.E (2002) “Extrusion cooking”, Chapter 14 in “The nutrition handbook for food processors” (eds) Henry, C. J. K and Chapman, C., Woodhead, Cambridge, England.

Campbell, A.J. (1997) “Food packaging”. Chapter 16 in “Food industries manual”, 24th edit., (eds) Ranken, M.D., Kill, R.C. and Baker, C.G.J., Blackie Academic & Professional, London.

Claesson, B. and Skjöldebrand, C. (2002) “Marketing report: Food sensors”, ABB Technical Report.

Cullen, P.J. (2009) (ed.) “Food mixing: Principles and applications”, John Wiley and Sons, Chitchester, UK, 292 pp.

Dagerskog, M. and Bengtsson, N.E. (1974) “Pan frying of meat patties: Relationship among crust formation, yield, composition and processing conditions”, Lebensmittel Wissenschaft und Technologie, 2023.

Ehlermann, D.A.E. (2002) “Irradiation”. Chapter 17 in “The nutrition handbook for food processors”, (eds) Henry, C. J. K. and Chapman, C., Woodhead, Cambridge, UK.

Fellows, P. (2009) “Food processing technology Principles and practice”, 3rd edit. Woodhead, Cambridge, UK, 575 pp.

Ginzburg, A.S. (1969) “Application of infrared radiation in food processing”, Leonard Hill, London.

Hallström, B. and Skjöldebrand, C. (1983) “Fundamental aspects of the transfer of heat to food” in “Developments in food preservation – 2”, (ed.) S .N. Thorne, Elsevier Applied Science , New York, NY, 328 pp.

Hallström, B., Trägårdh, C. and Skjöldebrand, C. (1988) “Heat transfer and food products”, Elsevier Applied Science, New York, 263 pp.

Harnby, N., Edwards, M.F., and Nienow, A.W. (2000) “Mixing in the process industries”, 2nd edit., Butterworth-Heinemann, Oxford, 414 pp.

Hesselman, K. (2012). “Trustworthy food for the future”, Speech at The Globe Forum, 26 April 2012, Stockholm, Sweden.

Holdsworth, S.D. (1997) “Food preservation processes”, Chapter 15 in “Food industries manual”, 24th edit., (eds) Ranken, M.D., Kill, R.C. and Baker, C.G.J., Blackie Academic & Professional, London.

Imre, L. (1997) “Solar dryers”. Chapter 10 in “Industrial drying of foods”, (ed.) Baker, C.G.J., Blackie Academic & Professional, London.

Jason, A.C. (1974) “Rapid thawing of foodstuffs”, IUFoST Proc., Madrid.

Masters, K. (1985) “Spray drying handbook”, Longman, London, 687 pp.

Masters, K. (2002) “Spray drying in practice”, SprayDryConsult Intl., Copenhagen, Denmark, 464 pp.

Pastair (2012) Land & Sjö Food Technology AB, Lund, Sweden. www.pastair.se.

Paul, E.L., Atiemo-Obeng, V.A., and Kestra, S.M. (2004) “Handbook of industrial mixing. Science and practice”, John Wiley and Sons, Hoboken, NJ, 1377 pp.

QB Food Tech (2012) Land & Sjö Food Technology AB, Lund, Sweden, www.qb.se.

Ranken, M.D., Kill, R.C., Baker, C.G.J. (1997) (eds) “Food industries manual”, 24th edit., Blackie Academic & Professional, London, pp. 219–221.

Riaz, M.N. (2000) (ed.) “Extruders in food applications”, CRC Press, Boca Raton, FL, 223 pp.

Richardson, P.S. (2000) (ed.) “Thermal technologies in food processing”, Woodhead, Cambridge, England, 294 pp.

Skjöldebrand, C. (1990) “Heat-induced water transport in solid foods during processing”, SIK Internal Report.

Skjöldebrand, C. (2000) “Infrared heating”. Chapter 9 in “Thermal technologies in food processing”, (ed.) Richardson, P.S., Woodhead, Cambridge, England.

Skjöldebrand, C. (2002) “Infrared processing”. Chapter 20 in “The nutrition handbook for food processors”, (eds) Henry, C.J.K. and Chapman, C., Woodhead, Cambridge, UK.

Sutherland, K. (2008) “Filters and filtration handbook”, 5th edit., Butterworth-Heinemann, Oxford, UK, 523 pp.

Chapter 4
Hygienic Design of Food-Processing Equipment

C.G.J. Baker

4.1 Introduction

Exemplary hygiene is an essential prerequisite for the manufacture of food that meets the high expectations of today's consumer in terms of safety, quality, and nutrition. The modern food factory must meet the stringent standards demanded both by national and local legislation and by retail customers. These focus principally on the following areas:

1. Any equipment used in food manufacture must be designed so as to permit efficient, safe, and hygienic operation, maintenance, and cleaning.
2. The equipment layout should also facilitate ease of operation, cleaning, and maintenance.
3. The equipment should be operated in a manner that is consistent with a high standard of hygiene.

This chapter is concerned primarily with the first two of these areas, namely, the hygienic design and layout of food-manufacturing equipment. This is a highly specialized subject and the author is indebted to Campden BRI in particular for permission to use and adapt relevant material contained in several of its technical reports.

It cannot be stressed too strongly that hygienic design is not an "optional extra"; it is fundamental to the safe and economic production of food. It should be an intrinsic feature of all equipment employed in food-manufacturing operations. Failure to appreciate this fact can result in food-poisoning and food-spoilage incidents, typical examples of which were quoted by ICMSF (1988) and are reproduced in Table 4.1. Subsequent attempts to correct basic design faults may not be fully successful and are invariably expensive. It therefore makes good commercial sense to ensure that any equipment purchased is fit for the purpose envisaged. Apart from the direct costs incurred in making any necessary modifications, indirect costs resulting from lost production and excessive downtime due to higher than necessary cleaning requirements may be even more daunting.

The findings of Campden's Hygienic Design Working Party were first published in 1982 and republished in 1992 (CCFRA 1992). In their report, the Working Party endorsed the seven basic principles for hygienic design (FDF/FMA 1967; Jowitt 1980) quoted below, which are equally valid today:

1. All surfaces in contact with food must be inert to the food under the conditions of use and must not migrate to, or be absorbed by, the food.

C.G.J. Baker (✉)
Chemical Engineering Department, College of Engineering and Petroleum,
Kuwait University, P.O. Box 5969 Safat, 13060 Kuwait
e-mail: christophergj.baker@gmail.com

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_4,

Table 4.1 Examples of the consequences of poor hygienic design

Equipment	Problem	Consequences	Correction
Grain silo	Areas of high moisture	Moldy grain[a]	Proper ventilation and grain turnover
Can reformer	Holes in cans of salmon	Botulism	Proper maintenance of equipment
Gelatin injector	Welds difficult to clean	Salmonellosis from meat pies	Smooth weld
Wood smoke sticks	Bacteria surviving cleaning	Spoilage of sausage	Replace wood with metal
Heat exchanger (cooling side)	Cracked cooling unit permitting entrance of contaminated water	Salmonellosis from milk powder	Replace heat exchanger
Pump	Worn gasket	Spoilage of mayonnaise	Replace gaskets more frequently
Deaerator	Not properly cleaned or located in processing scheme	Contamination of pasteurized milk; enterotoxigenic cheese	Properly clean deaerator and move upstream of pasteurizer
Commercial oven	Poor heat distribution	Areas of undercooking, rapid spoilage, potential food-borne illness	Correct heat distribution in oven, monitor temperature to detect failure

[a] Molds can produce a range of aflatoxins

2. All surfaces in contact with food must be smooth and nonporous so that tiny particles of food, bacteria, or insect eggs are not normally caught in microscopic surface crevices and become difficult to dislodge, thus becoming a potential source of contamination.
3. All surfaces in contact with the food must be visible for inspection, or the equipment must be readily disassembled for inspection, or it must be demonstrated that routine cleaning procedures eliminate the possibility of contamination from bacteria or insects.
4. All surfaces in contact with food must be readily accessible for manual cleaning, or if clean-in-place techniques are used, it must be demonstrated that the results achieved without disassembly are the equivalent of those obtained with disassembly and manual cleaning.
5. All interior surfaces in contact with food must be so arranged that the equipment is self-emptying or self-draining.
6. Equipment must be so designed as to protect the contents from external contamination.
7. The exterior or nonproduct contact surfaces should be arranged to prevent harboring of soils, bacteria, or pests in or on the equipment itself as well as in its contact with other equipment, floors, walls, or hanging supports.

In addition, the Working Party indicated that the following additional principles should also be applied:

8. In design, construction, installation, and maintenance, it is important to avoid dead spaces or other conditions which trap food, prevent effective cleaning, and may allow microbial growth to take place.
9. The requirement of guarding machinery to ensure safety in operation may easily conflict with hygiene requirements unless considerable care is taken in design, construction, installation, and maintenance.
10. Noise suppression is important in providing acceptable working conditions. However, many noise-reducing materials can give rise to microbiological or infestation problems unless care is taken in their selection, installation, and maintenance.
11. It is important that the equipment itself is so designed, installed, and maintained that it does not cause product contamination. Examples of possible contamination are lagging, which may break up, or insufficiently secured nuts and bolts. Such hazards should be designed out of the system.

This chapter is divided into three parts. The first considers the materials of construction that are used in food-processing equipment. The second addresses the fundamentals of hygienic design and, finally, the third cites typical examples of good and unsatisfactory practice.

4.2 Materials of Construction

4.2.1 Selection

The first, and arguably the most important, step in formulating a hygienic design is the selection of appropriate materials of construction. The requirements have been summarized by Thorpe and Barker (1985):

> Good sanitary (hygienic) design of equipment used in the manufacture of foods and beverages requires that all surfaces in contact with the product must be nontoxic, inert under the conditions of use, must not have constituents which migrate or are absorbed by the product, and, in addition, must be resistant to (i.e., inert to) cleaning and disinfecting agents under normal (or expected) conditions of use.

Within the EU, all materials intended to come into contact with foods must conform with (EC) 1935/2004 (EC 2004).

Stainless steels are widely used in the construction of food-processing equipment and may be employed safely in contact with foods. The proper choice of stainless steel will ensure that it is resistant to corrosion and inert under the conditions to which it is subjected. The most commonly used stainless steels are austenitic in character; their properties are summarized in Table 4.2. Austenitic stainless steels are chromium–nickel alloys, which are non-hardenable by heat treatment. They have a very high corrosion resistance to most foods and cleaning agents and do not discolor products. The most commonly used types are 304 and 316. These are 18-8 steels, which contain around 18 % chromium and at least 8 % nickel. Type 304, containing 0.06 % carbon, is extensively

Table 4.2 Stainless steels commonly used in the construction of food-processing equipment

AISI grade	Composition (%)	Properties	Comments
304	Cr 18.0–20.0, Ni 8.0–12.0, C 0.08 (max)	Moderate corrosion resistance A general purpose steel	
304L	Cr 18.0–20.0, Ni 8.0–12.0, C 0.03 (max)	A low-carbon version of type 304 Used for applications involving welding, as no subsequent annealing is required	
316	Cr 16.0–18.0, Ni 10.0–14.0, C 0.08 (max), Mo 2.0–3.0	Good corrosion resistance Resistant to pitting	Mo improves general corrosion and pitting resistance and also high-temperature strength compared to basic general purpose steels (e.g., type 302)
316L	Cr 16.0–18.0, Ni 10.0–14.0, C 0.03 (max)	A low-carbon version of type 316 Used for applications involving welding, as no subsequent annealing is required	
321	Cr 17.0–19.0, 9.0–12.0, C 0.08 (max), Ti 5×C (min)	Used for large welded structures, which cannot be annealed after welding	Stabilized with titanium to permit use in the 420–870 °C range

Adapted from Peters et al. (2003)

used in the manufacture of pipelines, storage tanks, and a wide range of dairy-processing equipment. A low-carbon variety, 304L, has improved welding properties. Type 316 has an increased nickel content (~10 %) and contains 2–3 % molybdenum. The latter greatly enhances its corrosion resistance and makes it particularly suitable for use with highly corrosive products.

Process equipment constructed from stainless steel is considerably more expensive than that from carbon steel: typically by a factor of 2–4 depending on its type, design features, and size (Peters et al. 2003). The cost of type 316 is greater than that of type 304. Table 4.3 lists equivalent 304 and 316 stainless steel grades in several different countries.

A number of other materials are used in the construction of food-processing equipment. Some of the more common ones are listed in Table 4.4. The proposed application should always be considered in assessing their suitability. As well as the product in question, the process conditions, and any proposed cleaning and sanitizing agents, should all be taken into account. A summary of sources of information on a large number of materials of construction has been compiled by Shapton and Shapton (1998). The corrosion resistance of a variety of the more common materials of construction, including many of those listed in Tables 4.2 and 4.4, has been summarized in Chemical Engineers' Handbook (Green and Perry 2008). Table 4.5, adapted from Shapton and Shapton (1998), gives an overview of the effect of detergent materials on different surfaces. The authors point out, however, that it should be used with caution since, for example, stainless steels display a range of properties.

A number of common materials, and product containing them, should *not* be used in food manufacture. These include lead; cadmium; antimony; chromium and nickel platings; zinc or galvanized iron; plastics containing formaldehyde, free phenol, or plasticizers; enamel; and wood. If you are in any doubt as to the suitability of any particular piece of equipment or consumable item, always seek further information from the supplier.

Where equipment is constructed from two different metals, an electric potential may be set up between them if they are both in contact with a conducting liquid. Under these conditions, one of the metals will dissolve preferentially in the liquid and deposit on the other. This is known as galvanic action and can result in severe corrosion. Which metal dissolves is determined by its position in the electromotive series. A partial listing of metals arranged in decreasing order of their tendency to ionize and pass into solution is given in Table 4.6. Thus, zinc, for example, is higher in the electromotive series than iron and will therefore preferentially dissolve. This explains the improved corrosion resistance of iron when it is galvanized (i.e., coated with a thin layer of zinc). Note that the tendency for corrosion increases as the difference in electrode potentials between different metals increases.

4.2.2 Surface Finishes

The importance of surface finish in hygienic design has been discussed at length by Timperley and Timperley (1993) in Campden Technical Memorandum No. 679. They noted that:

> The Machinery Regulations (1992) state that all surfaces must be smooth and that all surfaces in contact with foodstuffs must be easily cleaned and disinfected. Surfaces should, therefore, be continuous and free from cracks, crevices and pits, which could harbor product residues and/or microorganisms and possibly be retained after cleaning. Ideally, materials should be such that the original surface finish is retained during the working life of the equipment; this should include expected abuse as well as normal wear resulting from production. It should be noted that plastic materials are more easily abraded than metals and this may affect their cleanability.

Surface roughness R_a can be defined as the arithmetic average value of the departure of the profile above and below the mean line throughout the specified sampling length. Lelieveld et al. (2003) cite the following recommendations of both 3-A Sanitary Standards, Inc., in the USA and the European

Table 4.3 Equivalent stainless steel specifications in selected countries

USA	France	Germany	Italy	Japan	Russia	Spain	Sweden	UK	EU
AISI	AFNOR	W.N. 17007	UNI	JIS	GOST	UNE	SIS	BSI	EuroNorm
304	Z 6 CN 18-09	1.4301 1.4303	X 5 CrNi 1810	SUS 304	08KH18N10 06KH18N11	X 6 CrNi 19-10	23 32	304S15 304S16	X 6 CR Ni 18 10
304N			X 5 CrNiN 1810	SUS 304N1					
304H			X 8 CrNi 1910	SUS F 304H		X 6 CrNi 19-10			
304L	Z 2 CN 18-10	1.4306	X 2 CrNi 1911	SUS 304L	03KH18N11	X 2 CrNi 19-10	23 52	304S11	X 3 CrNi 18 10
	Z 2 CN 18-10-AZ	1.4311	X 2 CrNiN 1811	SUS 304LN			23 71		
316	Z 6 CND 17-11	1.4401	X 5 CrNiMo 1712	SUS 316		X 6 CrNiMo 17-12-03	23 47	316S31	X 6 CrNiMo 17 12 2
316	Z 6 CND 17-12	1.4436	X 5 CrNiMo 1713	SUS 316		X 6 CrNiMo 17-12-03	23 47	316S33	X 6 CrNiMo 17 13 3
316F		1.4427							
316N				SUS 316N					
316H			X 8 CrNiMo 1712	SUS F 316H		X 5 CrNiMo 17-12			
316H			X 8 CrNiMo 1713		03KH17N14M2	X 6 CrNiMo 17-12-03			
316L	Z 2 CND 17-12	1.4404	X 2 CrNiMo 1712	SUS 316L		X 2 CrNiMo 17-12-03	23 48	316S11	X 3 CrNiMo 17 12 2
	Z 2 CND 17-12-Az	1.4406	X 2 CrNiMoN 1712	SUS 316LN	03KH16N15M3				
	Z 2 CND 17-13	1.4435	X 2 CrNiMo 1713			X 2 CrNiMo 17-12-03	23 53	316S13	X 3 CrNiMo 17 13 3
	Z 2 CND 17-13-Az	1.4429	X 2 CrNiMoN 1713		08KH17N13M2T 10KH17N13M2T		23 75		
	Z 6 CNDT 17-12	1.4571	X 6 CrNiMoTi 1712		08KH17N13M2T 10KH17N13M2T	X 6 CrNiMoTi 17-12-03	23 50	320S31	X 6 CrNiMoTi 17 12 2
		1.4573	X 6 CrNiMoTi 1713		08KH16N13M2B	X 6 CrNiMoTi 17-12-03		320S33	X 6 CrNiMoTi 17 13 3
	Z 6 CNDNb 17-12	1.4580	X 6 CrNiMoNb 1712		09KH16N15M3B				X 6 CrNiMoNb 17 12 2
		1.4583	X 6 CrNiMoNb 1713						X 6 CrNiMoNb 17 13 3

Source: The Engineering ToolBox: www.EngineeringToolBox.com/stainless-steel-standards-d_445.html (last accessed 26 September 2011)

Table 4.4 Other permitted materials of construction

Material	Comments
Ferrous metals	
Carbon steel	May be used for conveyors, runways, machined components, structures, some storage tanks (plated or coated as necessary)
Cast iron	Not suitable for applications involving contact with product
Black iron	Suitable for fats where moisture content is low. Unsuitable for water-based pastes, fat–water emulsions, or confectionery syrups
Nonferrous metals	
Aluminum—food grade	Unsuitable for applications involving contact with brine, alkaline solutions (e.g., sodium carbonate, bicarbonate, hydroxide), strong acids
Copper and its alloys (brass, bronze, phosphor bronze)	May catalyze rancidity in oils and fats and cause vegetable discoloration or loss of vitamin C. Incompatible with some products and cleaning materials
Admiralty gunmetal	Unsuitable for acidic products (e.g., fruit juices), particularly those containing sulfur dioxide; incompatible with sodium bicarbonate. See also copper alloys
Monel metal	Suitable for syrups
Tinned copper	Suitable where copper is unsatisfactory. As tinning eventually wears off, stainless steel and aluminum are preferred
Tinned iron	Suitable for low-moisture-content fats, etc.
Plastics	
LDPE, HDPE (low- and high-density polyethylenes)	Sundry applications
GRP (glass-reinforced polyester)	Highly resistant to acids and alkalis. Commonly used for tanks
Rigid PVC (polyvinyl chloride)	Pipelines
ABS (acrylonitrile butadiene styrene)	Pipelines
Other materials	
Glass	Vulnerable to breakage and chipping. Only used where effective means are taken to avoid possible product contamination
Carbon	Used in seals. May contain harmful additives. Check with supplier
Rubber (natural and synthetic)	Food-grade quality may be used. Check with supplier

Hygienic Engineering & Design Group (EHEDG). Large surface areas in contact with foodstuffs should normally have a finish better than $R_a = 0.8$ μm. However, a roughness exceeding 0.8 μm may be acceptable if test results have demonstrated that the required cleanability can be achieved through other design features. A similar recommendation (i.e., $R_a < 0.8$ μm) was made for closed equipment used for handling liquids and normally cleaned-in-place. Again, exceptions can be made provided that the surfaces can be shown to be cleanable.

The surface finish of stainless steels is usually defined in terms of the manufacturing process to which they are subjected rather than the topography, i.e., R_a value (BSSA 2010). Provided it is free from pits, folds, and crevices, unpolished cold rolled steel sheet with a standard 2B finish (BSI 2005) is suitable for the construction of food-processing equipment. This has a roughness of 0.1–0.5 μm, which therefore satisfies the requirement that R_a should be less than 0.8 μm.

As pointed out by Timperley and Timperley (1993), it is generally recognized that rougher surfaces provide a better mechanical "key" for product soil and hence for the growth of microorganisms. Moreover, the initial assessment of the cleanliness of open process equipment is visual, and it should be noted that residual soil is more readily observed on bright surfaces than on dull ones; this should be taken into consideration when selecting the finish. Electropolishing of stainless steel is a cost-effective method of obtaining a bright finish but, as only 10 μm of metal is removed from the surface, it will not remove deep scratches.

Table 4.5 Effect of detergents on common materials of construction and finishes

Surface	Caustic soda	Meta silicate	Synthetic detergents	Phosphoric acid	Nitric acid	Hydrochloric acid	Sulfamic acid	Solvents	Sodium hypochlorite
Stainless steel				TC	X	X	TC		
Mild steel				TC	X	X	TC		T
Copper				TC	X	X	TC		TC
Zinc	X			X	X	X	X		X
Aluminum	X				X	X	X		TC
PVC					TC	TC	TC	X	
Polypropylene					TC	TC	TC	X	
Oil paint	X	C	C	–			–	X	
Emulsion paint	X	C		–			–	X	

Adapted from Shapton and Shapton (1998)

Notes apply unless detergent is specifically inhibited against attack on surface

X not suitable, *T* may be used at recommended temperatures, and *C* may be used at recommended concentration

Table 4.6 Electromotive series of selected metals

Metal	Ion	Standard electrode potential at 25 °C (mV)
Aluminum	Al^{3+}	1.70
Zinc	Zn^{2+}	0.76
Chromium	Cr^{2+}	0.56
Iron	Fe^{2+}	0.44
Nickel	Ni^{2+}	0.23
Tin	Sn^{2+}	0.14
Lead	Pb^{2+}	0.12
Iron	Fe^{3+}	0.045
Copper	Cu^{2+}	−0.34
Copper	Cu^{+}	−0.47
Lead	Pb^{4+}	−0.8.

Adapted from Peters et al. (2003)

In Campden Technical Manual No. 17, Timperley (1997) noted that there is no evidence to support earlier ideas that the surface finish of stainless steels is a critical factor in efficient cleaning of food-contact surfaces by direct impingement from spray jets, provided R_a is less than 1 μm. As a result, the electroplating of surfaces or components, for example, heat exchanger plates, is now less frequently employed.

4.2.3 Examples of Do's and Don'ts

The Campden Hygienic Design Working Party (CCFRA 1992) set out a series of "Do's" and "Don'ts" relating to good practice in various aspects of hygienic design. Those relating to materials of construction may be summarized as follows. Note that the numbering of examples does not signify their order of importance.

Do

1. *Do* ensure that materials of construction are suitable to withstand both food and cleaning materials under the operating conditions.
2. *Do* ensure that all internal surfaces are inert and nonporous and have an appropriately smooth finish.
3. *Do* check that, where gaskets are fitted to flanged joints, the gasket material is of food quality, nonabsorbent, non-tainting, and trimmed flush both internally and externally.
4. *Do* take care to ensure that paint and other surface treatments adequately protect the joint areas between machine components to prevent corrosion and subsequent contamination.
5. *Do* remember that materials less expensive than stainless steel may be used for some applications, e.g., mild steel may be used for conveyors or runways, aluminum for dry ingredient bins or trays, galvanized steel for machine supports and platforms, epoxy-coated mild steel for some dry ingredient storage, fiberglass for tanks, and polypropylene and polyethylene for some pipelines. However, the cost of supporting plastic pipelines so that they do not sag may be as expensive as installing stainless steel lines.
6. *Do* check that any dissimilar materials will not corrode.
7. *Do* make sure of product and cleaning material compatibility if phosphor bronze or gunmetal is used.

8. *Do* ensure that conveyor belt materials are carefully chosen. Where applicable, a PVC top surface and polyester carcass are preferred for cleaning and minimal microbial contamination. Care should be taken to ensure effective sealing or bonding at cut edges.

Don't

1. *Don't* use wood in construction where it might splinter or otherwise contaminate the product. Wooden surfaces are very difficult to clean and disinfect thoroughly.
2. *Don't* use glass lining where it may become chipped during normal use or cleaning.
3. *Don't* use glass where it may be broken and contaminate the products—e.g., gage or sight glasses.

4.3 Fundamentals of Hygienic Design

The detailed mechanical design of food-processing equipment is a vital element in ensuring safe and efficient operation. An effective hygienic design should protect the product from microbial, chemical, and foreign-body contamination. It should also permit effective and efficient cleaning to be performed.

In this section, some of the more important aspects of hygienic equipment design are described. It is clearly not possible within the allocated space to cover all aspects in fine detail, nor is it necessary. Its primary purpose is to acquaint the reader with the more important principles involved, which will provide him (or her) with sufficient background to discriminate between good and inadequate designs. Perhaps most importantly, it should enable him to identify suitable equipment suppliers, who have the necessary expertise in hygienic design and construction and are familiar with the requirements of the industry.

Before entering into a description of the principal features that underlie the hygienic design of food-processing equipment, it is perhaps useful to consider some of the factors that affect bacterial growth on surfaces. To grow, bacteria require nutrients, a suitable temperature, and moisture. In many situations, these requirements are more than adequately met in plant and machinery used in food manufacture. The bacterial growth forms a film, which is attached to surfaces that are frequently in contact with the food being processed. Individual bacteria become detached from the surface, thereby contaminating the product. The film is often referred to as "soil." This term is not restricted to bacterial contamination; it may also be used to describe undesirable organic or inorganic material, including food that becomes attached to or covers a surface.

The bacterial soil can be removed and destroyed fairly easily on smooth exposed surfaces by the application of a suitable sanitation program. However, where surfaces are rough, porous, or corroded, it is more difficult, if not impossible, to clean and disinfect them effectively. Many bacterial cells are about 1 μm in diameter. Water and dissolved nutrients can penetrate a gap of this size at, for example, a joint or overlapping surfaces. Bacteria growing in the gap are very difficult to remove or destroy using normal cleaning techniques and provide a focus for reinfection of a cleaned surface. "Dead spots," in which product is able to accumulate for a length of time before eventually being swept back into the flow, also provide ideal sites for bacterial growth.

Table 4.7 (Timperley 1997) illustrates typical microbial counts after cleaning. Standards differ according to the product and the processing technology employed. The figures given in Table 4.7,

Table 4.7 Typical numbers of organisms on surfaces after cleaning

Grade	Per square decimeter	Per square foot
Satisfactory	0–540	0–5,000
Fairly satisfactory	540–2,700	5,000–25,000
Unsatisfactory	>2,700	>25,000

which are based on dairy standards for the cleanliness of product-contact surfaces, provide a guideline for general purposes. In some situations, however, they may not be sufficiently stringent.

Although microbiological concerns undoubtedly dominate the engineering design effort, chemical and foreign-body contamination should not be overlooked. For present purposes, chemicals include cleaning and sanitizing materials, and dust and other atmospheric contamination may be classed as foreign bodies. Hygienic design should also address the ease of dismantling the equipment for cleaning and maintenance. It should provide an appropriate balance between the need to provide for cleanliness and hygiene, on the one hand, and mechanical and electrical safety on the other.

See Brougham (2011) for a detailed description of cleaning and disinfection systems.

4.4 Design Principles

This section details some of the more important principles of hygienic design. The examples cited have been taken from Campden Technical Memorandum No. 679 (Timperley and Timperley 1993). Although the latter focuses on meat-slicing machines, the information presented is of general validity.

4.4.1 Permanent Joints

The Machinery Regulations (1992) state that “assemblies,” i.e., the joining of two or more parts, should preferably be made by welding or continuous bonding so as to reduce projections, edges, and recesses to a minimum. They also state that “the joint must be smooth and must have neither ridges nor crevices which could harbor organic materials.”

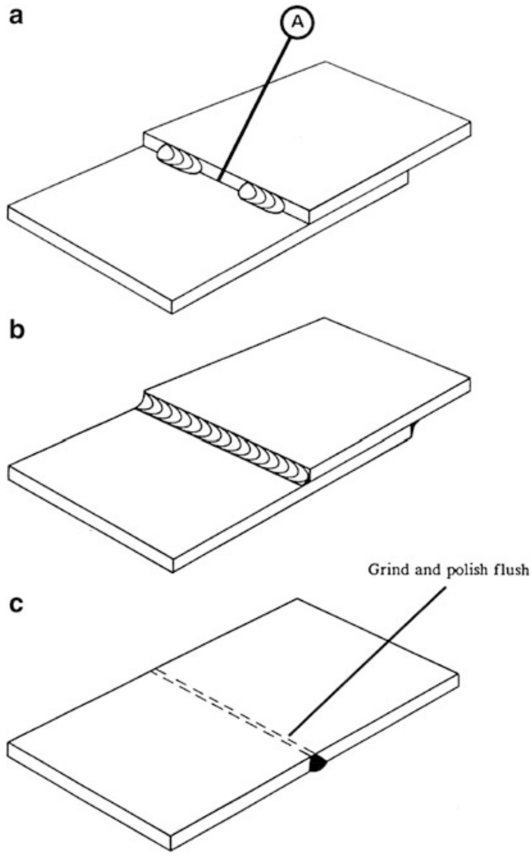
It is recognized that, in some cases, continuous welding may result in unacceptable distortion. In this case, intermittent welds may be employed. These create crevices and may retain product residues and harbor microorganisms, which cannot be removed or destroyed; these may subsequently grow out and contaminate the product. Permanent joints can be sealed effectively by other methods such as silver soldering but the solder must not contain cadmium. It may be necessary to employ both welding for strength and silver soldering for sealing. Welds must be ground and polished to a standard of finish equal to that of the surrounding material.

When two pieces of metal are to be joined together by welding, they should not be lapped because, as shown in Fig. 4.1a, b, a ridge is formed which makes cleaning more difficult. An uncleanable crevice is created at (A) if the joint is intermittently welded (Fig. 4.1a). While a continuous weld, as shown in Fig. 4.1b, would eliminate the crevice, there would still be a ridge even if the filled weld were to be ground and polished. Wherever possible, the two pieces should be butt welded, as shown in Fig. 4.1c, and the surface on the product side ground and polished to the same finish as that of the adjacent surfaces.

4.4.2 Semipermanent Joints

From a manufacturing viewpoint, many components have to be made individually and fixed together by means of fasteners, such as bolts and screws. Many of these joints are of a semipermanent nature and are not routinely broken, e.g., on a daily or even weekly basis, for cleaning. Such joints may

Fig. 4.1 Examples of hygienic and unhygienic welded joints



harbor product residue and high microbial counts. Hence, all such joints must be sealed against the ingress of product, liquids (from cleaning), and microorganisms by means of a gasket. It is recommended that, where possible, a gasket material such as the FDA-approved GYLON is used; controlled compression of gaskets is, of course, essential. In certain cases, the mating surfaces are coated with a silicone rubber sealant prior to assembly. However, it has not yet been proven how effective and lasting this technique is.

The semipermanent joints shown in Fig. 4.2 are used as a means of construction and are not intended for frequent disassembly. Uncleanable crevices are denoted by (A). In both (a) and (b), unhygienic fastening arrangements are employed; see Sect. 4.4.3.

Figure 4.3 shows what is claimed by Timperley and Timperley (1993) to be potentially the most hazardous part of a meat-slicing machine from the microbiological view. It is referred to as the shear edge and is a strip of material attached by screws to the end of the log feed bed. It is usually constructed from plastic because the blade passes over its end face, and any other harder material could cause damage to the blade if contact was made. There is a crevice in the joint at (A), Fig. 4.3a, between the plastic and metal. In all instances where the shear edge is not removed for cleaning on a daily basis, this crevice has been found to contain residual product and is a potential site for the growth of pathogenic microorganisms.

The example shown in Fig. 4.3a is also secured in an unhygienic manner by means of recessed head socket screws. A more hygienic arrangement is shown in Fig. 4.3b in which thread inserts have been used in the plastic and hexagonal-headed screws inserted from the nonproduct side.

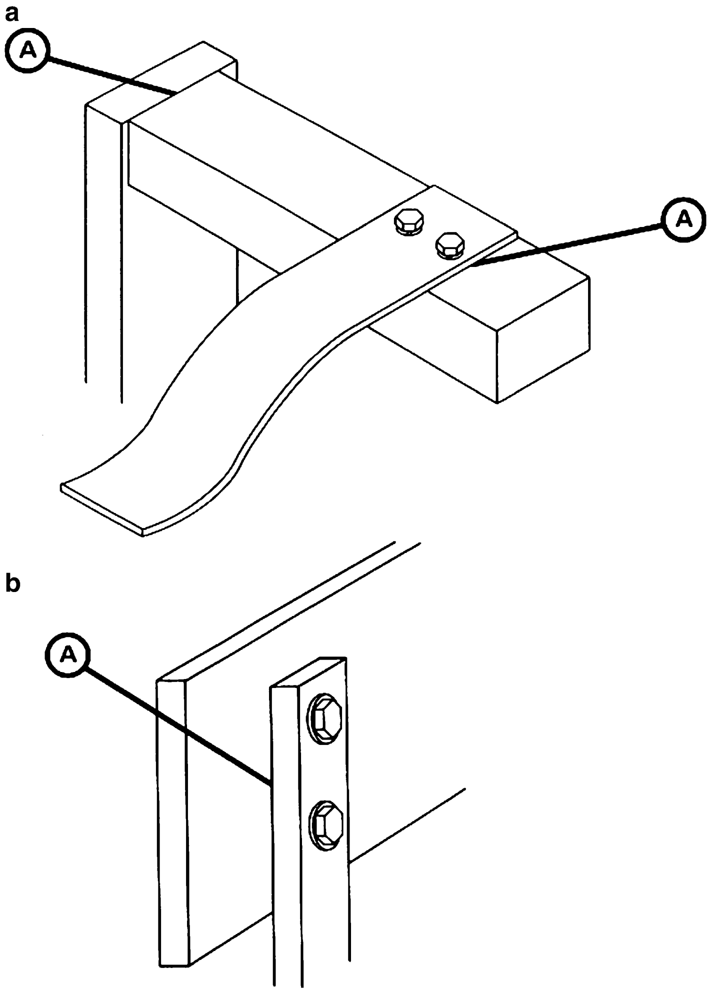


Fig. 4.2 Examples of unhygienic semipermanent joints

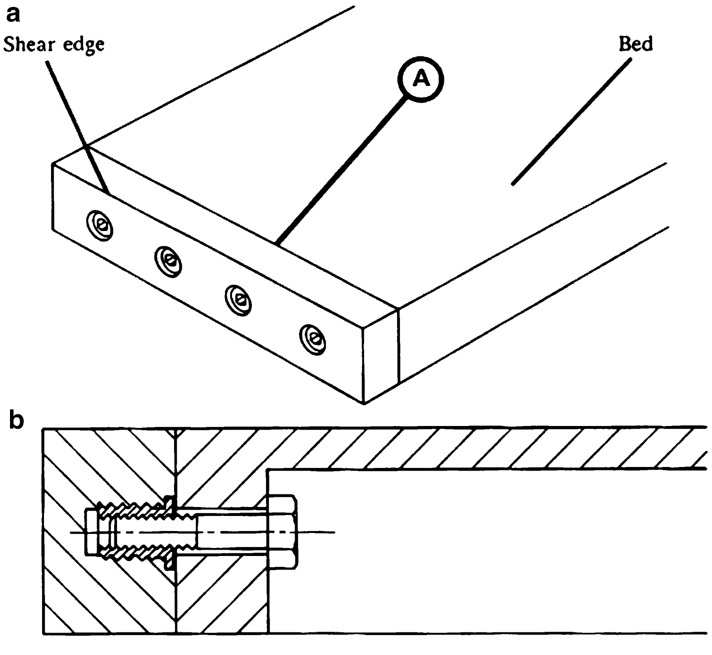


Fig. 4.3 Shear edge of a meat-slicing machine

4.4.3 Fasteners

It is stated in the Machinery Regulations (1992) that screws, screwheads, and rivets may not be used except where technically unavoidable. Due to the complexity of many food-processing machines, particularly those containing rotating parts, many components have to be assembled by means of screws and bolts. Many of these present a potential hygiene hazard because the slots or sockets in the heads can retain product, which may be difficult to remove. The metal–metal joint between the head and the surface can permit the ingress of microorganisms, which may subsequently multiply.

Where fasteners are removed on a daily basis, to remove components or assemblies for cleaning purposes, for example, they are unlikely to give rise to hazardous conditions. However, fasteners that are cleaned infrequently may give rise to hygiene problems.

In some situations it is necessary to prevent nuts and screws from coming loose. This is usually achieved by the use of spring washers; these present a further potential problem because of the gap between the ends. It is suggested that thread locking compound be used instead.

Figure 4.4 shows typical examples of unhygienic fasteners. The illustrations depict hexagon socket head cap screws (a and b), countersunk head screws (c and d), a hexagon socket round head screw (e), and, finally, a recessed hexagon head screw (f). In each case, the sockets (in a, b, d, and e) and the screwdriver slot (in c) may retain product residues. In every case, there is also an unsealed metal–metal joint, denoted by (B). Finally, in (f), there is a large annular space (C), which may also retain product residues.

Figure 4.5, in contrast, illustrates examples of hygienic fastenings. In (a) and (b), the fastenings are on the nonproduct side. If, as shown in (a), the metal on the product side is thin, then a stud can be welded to the nonproduct side to secure the component. However, if the metal on the product side is thicker, a blind hole can be tapped so that the component may be secured by a screw inserted from the nonproduct side, as shown in (b). The effective sealing of metal/metal joints under hexagon heads is illustrated in (c) and (d). Here, a metal-backed rubber washer is used to prevent the ingress of microorganisms. This consists of a metal ring around which a wedge-shaped rubber ring is bonded. The head of the hexagon screw is shown just making contact with the outer edge of the rubber in (e). The screw is shown fully tightened in (f); the inner metal ring prevents over-compression of the rubber and allows the required tightening torque to be applied.

4.4.4 Drainage

The Machinery Regulations require that liquid deriving from foodstuffs should be capable of being discharged from the machine without impediment. The same is true of cleaning, disinfecting, and rinsing fluids. Examples of properly engineered equipment are given in Sect. 4.5.

4.4.5 Internal Angles and Corners

The Machinery Regulations require that inside surfaces have curves of a radius sufficient to allow thorough cleaning. Although no value can be given, especially as a radius may not be technically achievable, it should be as large as possible. A radius can be obtained when metal is bent or machined but, when components are bolted or screwed together, a sharp corner is usually

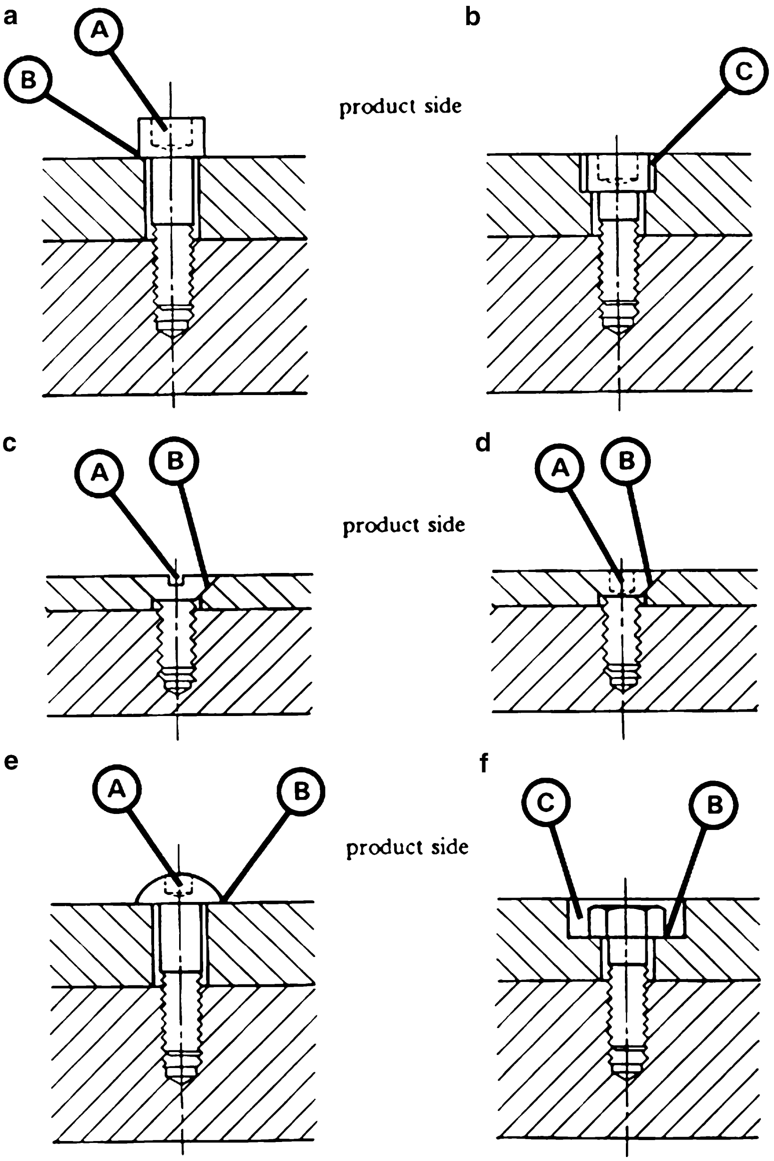
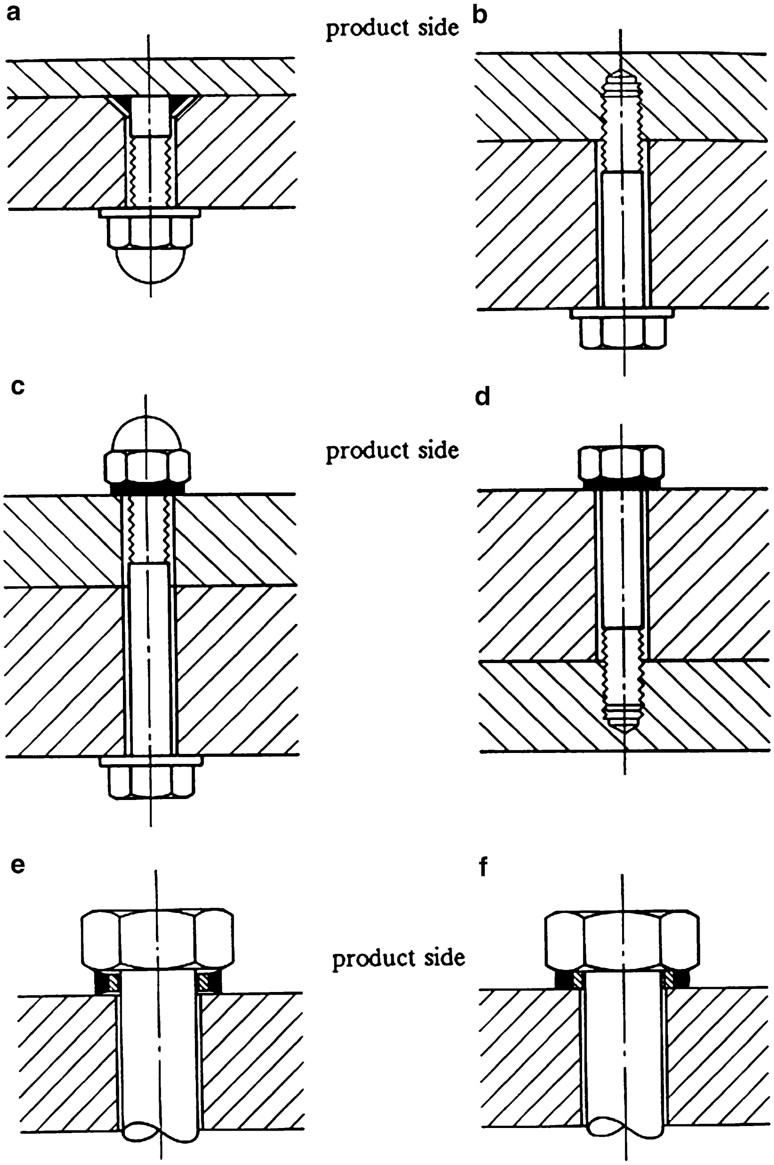


Fig. 4.4 Examples of unhygienic fasteners

unavoidable. Such arrangements in product areas should be avoided in the design or kept to a minimum unless the components are routinely removed for cleaning.

Figure 4.6 shows examples of different internal corners. In (a), the weld is on the product side and is both difficult to clean and difficult to grind and polish. As a result, it should be avoided. In (b), the weld is on the nonproduct side. This results in a crevice (A) that is difficult to clean; this method of fabrication should therefore also be avoided. Where possible, the metal should be bent to form a smooth, easy to clean radius, as shown in (c). If, as in (d), a joint is necessarily close to an internal angle, then the metal should be bent and a butt-welded joint made away from the corner. This can be more easily ground and polished flush to the same finish as that of the adjacent surfaces.

Fig. 4.5 Examples of hygienic fasteners



4.4.6 Dead Spaces

Dead spaces are those parts of the equipment in which product residues or cleaning fluids can be retained and subsequently contaminate the product. The Machinery Regulations state that equipment must be designed and constructed so as to prevent the ingress of liquids and living creatures (e.g., insects) into any areas that cannot be cleaned. In addition, organic matter must not be permitted to accumulate in such areas. In practice, this means that any space within a machine must be effectively sealed by means of a suitable gasket or be designed for regular dismantling to permit the space to be cleaned and disinfected. The gasket material must, of course, be approved for food-contact applications if it is in the product zone, and its condition should be checked periodically because some materials such as rubber eventually harden and crack in service.

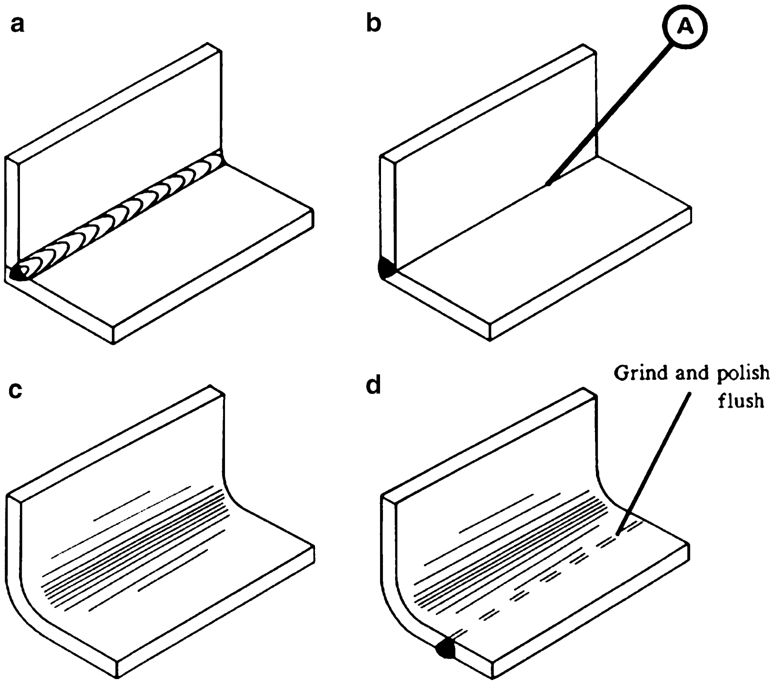


Fig. 4.6 Examples of good and bad internal angles and corners

4.4.7 *Bearings and Shaft Seals*

The Machinery Regulations require that machinery must be designed and constructed so as to prevent ancillary substances (e.g., lubricants) coming into contact with foodstuffs. In addition, provision must be made to ensure that, where necessary, continuing compliance with this requirement can be checked. Bearings should be either of the "sealed-for-life" or "double-sealed" variety and should be located external to the equipment in order to minimize contact with product. Bearing covers should be fitted where possible. Note, however, that seals ultimately wear and leak. Their condition must therefore be monitored regularly and they must be replaced periodically as part of planned maintenance programs.

It is essential that noncompatible lubricants should not come into contact with the product. Therefore, where possible, edible greases such as acetylated monoglycerides should be employed. It is advisable to avoid steam cleaning of lubricated bearings. If this is essential, they should be allowed to dry out before they are relubricated. Any excess lubricant should be removed.

In order to prevent damage to the seals, they should also be designed so as to minimize the ingress of product particles. In many cases, however, the total exclusion of particles is not economically possible. Under these circumstances, the seals should be subject to frequent cleaning.

4.4.8 *Controls*

The operator who operates the controls often handles product. As a result, contamination from residual product on controls can be transferred to fresh product immaterial of whether the operator wears gloves or not. Controls must therefore be of hygienic design so that they can be maintained in a

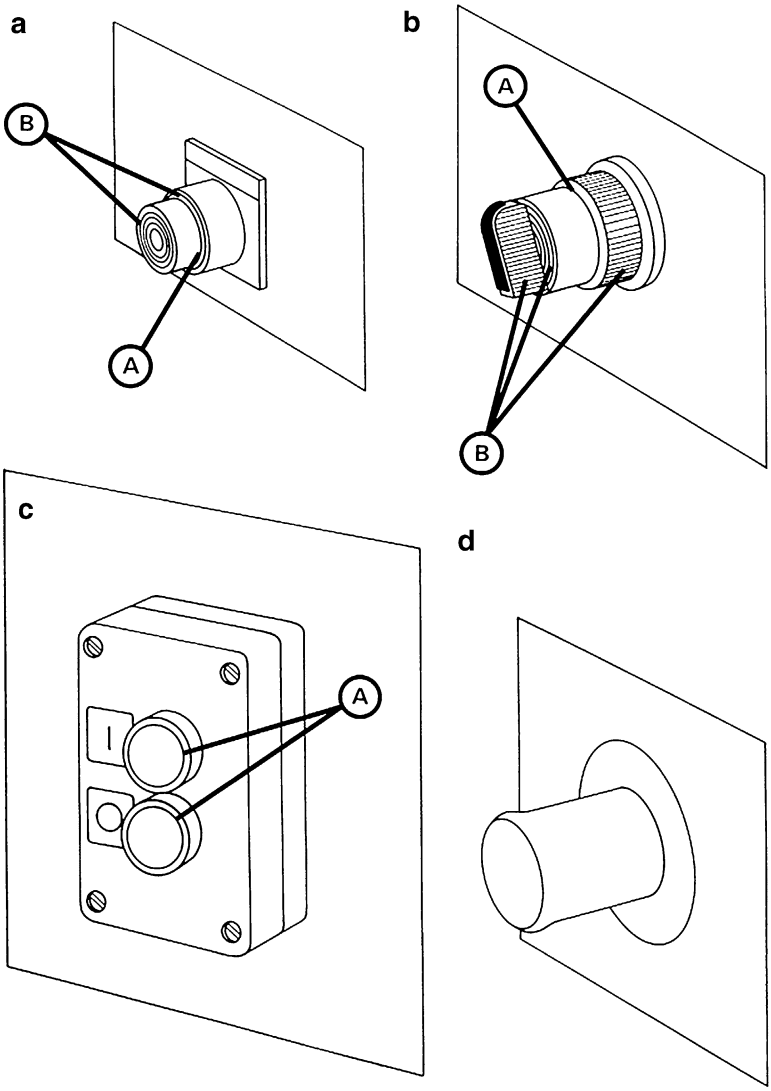


Fig. 4.7 Examples of hygienic and unhygienic controls

clean condition. It goes without saying that they must be capable of withstanding whatever cleaning regime is used on the entire machine; this may involve high-pressure water jetting.

Most push buttons and rotary selector switches have many uncleanable crevices. Although protective caps can be fitted to push buttons, which does give some improvement, the ends often become split by fingernails. Wherever possible, touch panels having a membrane covering should be used, as these can be easily kept clean throughout production periods by the regular use of disinfectant-impregnated disposable wipes.

Some examples of good and bad controls are shown in Fig. 4.7. The type of push button switch shown in (a) has an uncleanable annular crevice (A) and grooves that are difficult to clean (B). The fitting of a protective rubber cap would be an improvement, but its condition would have to be checked regularly. The rotary selector switch (b) suffers from similar deficiencies: an uncleanable annular crevice (A) and difficult-to-clean grooves (B). A protective rubber sleeve fitted at the base of the switch would provide only partial improvement. Although a protective rubber cap would cover the uncleanable annular crevices (A) in (c), the cap in this instance is very prone to damage from fingernails because the end of the push button is flush with the fixed outer sleeve. In addition, the recessed screws would be difficult to clean.

The construction of the emergency stop button shown in (d) is such that it is totally enclosed and meets the requirements of the Machinery Regulations in that it has to be pulled out to reset it. It is protected against the ingress of water and its smooth profile makes it easy to clean.

4.4.9 Equipment Location and Installation

The discussion to date has concentrated on individual items of equipment. In practice, hygiene is also affected by their location and installation and these aspects also require detailed consideration. A number of important points that should be taken into consideration have been listed in Campden Technical Manual No. 17 (Timperley 1997). These were elaborated by Shapton and Shapton (1998).

1. There should be sufficient height to allow adequate access for inspection, cleaning, and maintenance of the equipment and cleaning of the floors.

   In practice, small items of equipment, including motors and gearboxes, should be mounted at least 200 mm off the floor (Foresythe and Hayes 2000). Larger items require a greater clearance. Shapton and Shapton (1998) concur with the recommendation of Ridgeway and Coulthard (1980) that this should be sufficient to allow a brush, held at 30° to the horizontal, to reach the center line of the machine. This permits the floor underneath the equipment to be fully cleaned from both sides without the cleaner having to stoop.
2. All parts of the equipment should be installed at a sufficient distance from walls, ceilings, and adjacent equipment to allow easy access for inspection, cleaning, and maintenance, especially if lifting is involved.

   In practice, there should be a minimum clearance of 1 m between the equipment and the nearest wall, ceiling, and adjacent plant item.
3. Ancillary equipment, control systems, and services connected to the process equipment should be located so as to allow access for maintenance and cleaning.

   Shapton and Shapton (1998) cite ICMSF (1988):

   > It is worth repeating an earlier observation about the need properly to encase and waterproof all electrical and other service or control facilities/connections; leakage from conduits can be a potent source of contamination. Similarly it is important to install liquid flow connections, such as vacuum breakers, that do not permit back-siphonage of liquids, as this can lead to microbiological contamination of processed product by unprocessed product or even by waste water.

   Note that mounted switchgear should be either sealed to the wall (the preferred option) or mounted with a minimum clearance of at least 500 mm from it. All electrical equipment should be sealed to a minimum of IP65 in wet areas and IP5 elsewhere.
4. Supporting framework, wall mountings, and legs should be kept to a minimum. They should be constructed from tubular or box-section material, which should be sealed to prevent ingress of water or soil. Angle- or channel-section material should not be used.

   To prevent the collection of soil on flat surfaces, horizontal square tubing should be rotated through 45°.
5. Base plates used to support and fix equipment should have smooth, continuous, and sloping surfaces to aid drainage. They should be coved at the floor junction. Alternatively, ball feet should be fitted.
6. Pipework and valves should be supported independently of other equipment to reduce the chance of strain and damage to the equipment, pipework, and joints.
7. Avoid draining equipment directly onto the floor.

8. Avoid, as far as possible, installation practices that introduce, for example, ledges and soil traps, recess corners, spot, or tack welds, which result in incompletely sealed seams and projecting bolt threads.

Katsuyama and Strachan (1980) advise the following: tubular support braces should be welded to structural members; open tubes should be capped; drilling into tubes should be avoided.

Campden Technical Memorandum 17 notes that in situations where soil trapping occurs because of inadequate attention to hygienic design or installation, there is a real likelihood that:

1. Cleaning operations will involve more time and increased costs.
2. Clean-in-place (CIP) procedures may not remove all soil deposits.
3. Failure to remove soil may result in microbial growth and contamination of products.
4. The risk of a corrosion attack associated with retained soil will be increased.

4.4.10 Examples of Do's and Don'ts

The Campden Hygienic Design Working Party (CCFRA 1983) set out the following "Do's" and "Don'ts" relating to good practice in hygienic design, cleaning, and sanitation.

Do

1. *Do* ensure that all surfaces in contact with food are completely self-draining and can be easily and quickly reached to ensure adequate cleaning.
2. *Do* ensure that all pumps and valves in contact with food are of sound mechanical and hygienic design, that the surface finish meets the required specifications, and that the installation is hygienic and will allow complete drainage.
3. *Do* ensure that tank inlets and outlets are flush with interior surfaces and are self-draining.
4. *Do* ensure that there are no internal filth traps around any stirrer, probe, or level-control fittings inside tanks.
5. *Do* seal the ends of all hollow-section frames wherever used.
6. *Do* position framework members and brackets so as to avoid horizontal flat surfaces wherever possible.
7. *Do* keep machine design as open as possible and avoid dark, difficult-to-reach corners.
8. *Do* ensure that any oil drip trays that are provided under motors and gearboxes can be drained and cleaned.
9. *Do* make product catch trays large enough, slope them to drain at the lowest point, provide them with a big enough drain to avoid blockage, and make it accessible for visual inspection, especially after cleaning.
10. *Do* ensure that proper provision is made at the design stage for waste and effluent removal.
11. *Do* design conveyors so that the belt can be readily slackened, thereby allowing it to be raised clear of the bed for cleaning.
12. *Do* design the cleaning programs as part of the installation right from the start.
13. *Do* ensure adequate access for hose cleaning when ensuring that guarding complies with health and safety requirements.
14. *Do* leave adequate clearances under and around machinery to allow for effective cleaning and ensure that floor-bearing surfaces are either sealed or can be cleaned.
15. *Do* ensure that movable joints and hinges can be easily cleaned.
16. *Do* plan to clean in place if possible—including conveyors and elevators in addition to tanks, pipework, and other equipment.

17. *Do* remember that some items of equipment and installations such as ball valves and horizontal pipelines are particularly difficult to clean.
18. *Do* design for the hygienic installation of control equipment and cables.

Don't

1. *Don't* use a socket head or other screws where these might constitute a product trap point.
2. *Don't* drill into hollow sections where product contamination could occur.
3. *Don't* allow soil-trapping ledges over the product path.
4. *Don't* create "dead spots" where product may be retained for a time and subsequently dislodged back into the system.
5. *Don't* allow any surfaces to harbor any form of dirt, oil, or grease.
6. *Don't* place vulnerable electrical equipment where damage may arise during washing or cleaning operations.

4.5 Examples of Hygienic Design

This section describes several examples of the proper application of the design principles described above. Taken mainly from Campden reports, they focus on pumps, pipework, and fittings (Timperley 1997), post-process can handling (Thorpe and Barker 1985) and product transfer in fruit and vegetable processing lines (CCFRA 1983). Only a brief overview of these topics is possible here because of space limitations. The reader is therefore referred to the original documents for full details.

4.5.1 Pumps

Many types of pump are used in the food industry for applications such as filling, emptying, transferring, and dosing. The choice of pump for any given application depends primarily on the characteristics of the material to be pumped; of particular importance are its rheological properties and its sensitivity to shear. There are, broadly speaking, two classes of pump, which are widely employed in the food industry. Rotodynamic (centrifugal) pumps are used for transferring low-viscosity liquids at relatively high flow rates but at comparatively low heads. Positive displacement pumps, of which there are many types (e.g., lobe, gear, vane impeller, and progressive cavity), are capable of handling high-viscosity and shear-sensitive liquids; several are capable of pumping liquids containing suspended solids with minimal damage.

The choice of a particular pump naturally depends primarily on the type of product being handled and the required process duty. However, in food-industry applications, due attention must also be paid to its hygienic design to ensure that the surface finish is adequate, that there are no crevices or dead spots in which product can be retained, and that the pump casing can be properly drained.

In the food industry, the materials of construction most commonly used for product-contact surfaces in pumps are 304 and 316 stainless steels. In some cases, elastomers and plastics are also used. These should, of course, be compatible with the products to be handled, including detergents and disinfectants, and comply with all relevant legislation relating to materials in contact with food. They should also be capable of withstanding the maximum envisaged process temperature; this will exceed 100 °C if steam sterilization is employed. There are no specific standards for the internal surface finish of pumps. In practice, a roughness similar to that recommended for the internal surfaces of pipes (less than 1 μm R_a) is commonly employed.

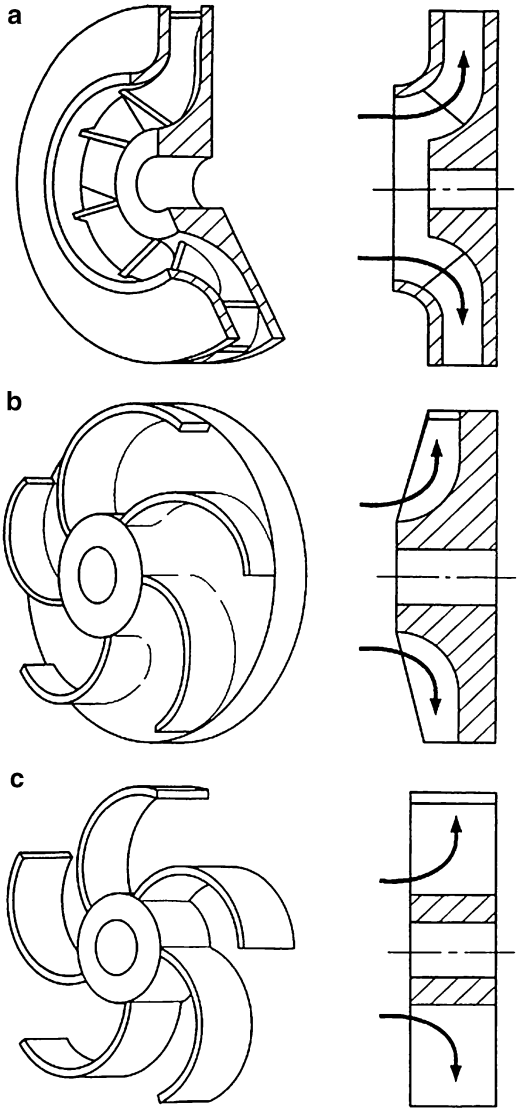


Fig. 4.8 Types of centrifugal pump impeller

By way of example, we will now consider the application of hygienic design principles in relation to centrifugal pumps. The reader is referred to Timperley (1997) for similar details relating to several types of positive displacement pump.

Centrifugal pumps are widely used in the food industry. They are of simple design and relatively inexpensive. Liquid is directed into the eye of an impeller rotating at around 3,000 rpm, which elevates both its pressure and velocity. On leaving the impeller, it is directed into a volute-shaped casing from which it is discharged tangentially. Mechanical seals are widely used to seal the shaft. A single seal is adequate for hygienic design purposes but a double seal is required for aseptic duties. In this case, the space between the two seals is continuously flushed with either steam or antimicrobial fluid.

The typical types of impeller and shroud shown in Fig. 4.8 illustrate well the compromises that have to be made to ensure a hygienic design. The fully shrouded impeller (a) is the most efficient from a mechanical viewpoint, but the channels cannot be polished economically. The unshrouded impeller (c) is the least efficient but is the easiest to polish. The partially shrouded design shown in (b) represents an acceptable compromise between (a) and (c). An alternative design features a fully

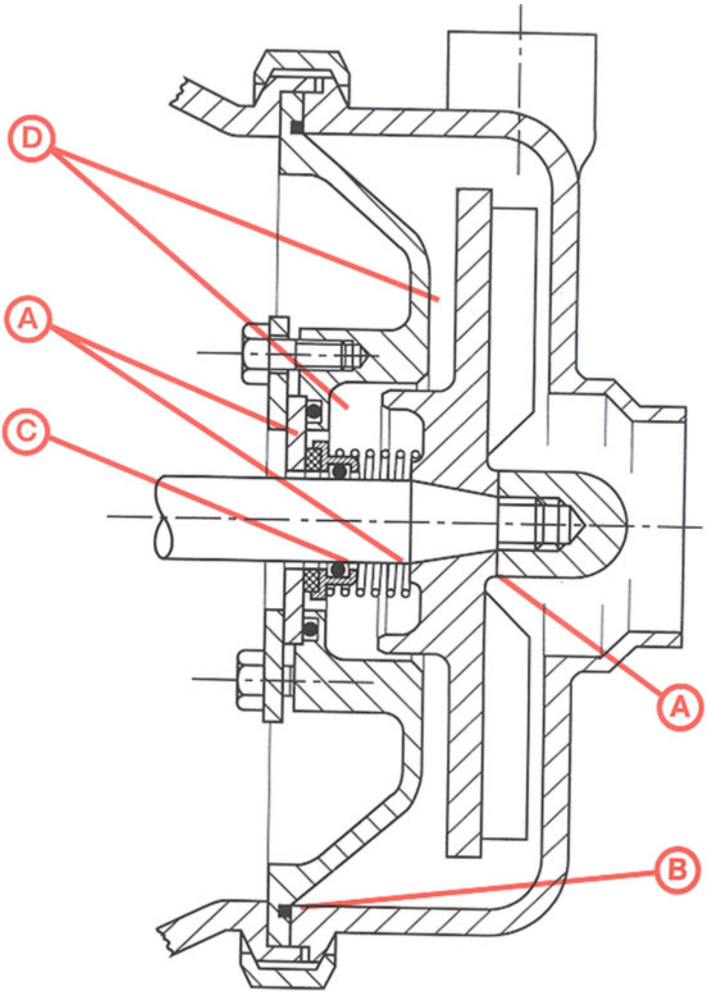


Fig. 4.9 Centrifugal pump—unhygienic design features

shrouded impeller with a detachable front shroud in an attempt to achieve the best of both worlds. However, it features metal–metal joints between the impeller body and the front shroud and must therefore be regarded as questionable from a hygienic point of view because these are very difficult to clean in place satisfactorily.

Figure 4.9 illustrates a number of design features that could create hygiene problems in a centrifugal pump; suggested improvements are shown in Fig. 4.10. The two designs are compared in Table 4.8.

As noted above, complete draining of pumps is an essential hygienic design feature. In order to achieve this, correct orientation of the pump is necessary. While it is often convenient to mount the pump with its outlet port pointing vertically upwards, this will result in liquid being retained in its casing. The casing will drain if the outlet is oriented horizontally at the bottom of the pump.

4.5.2 Pipelines and Fittings

In large liquid processing plants, the pipework can amount to a considerable proportion of the surface in contact with the product. The correct selection and installation of such pipework and its associated fittings is therefore of prime importance in maintaining plant hygiene.

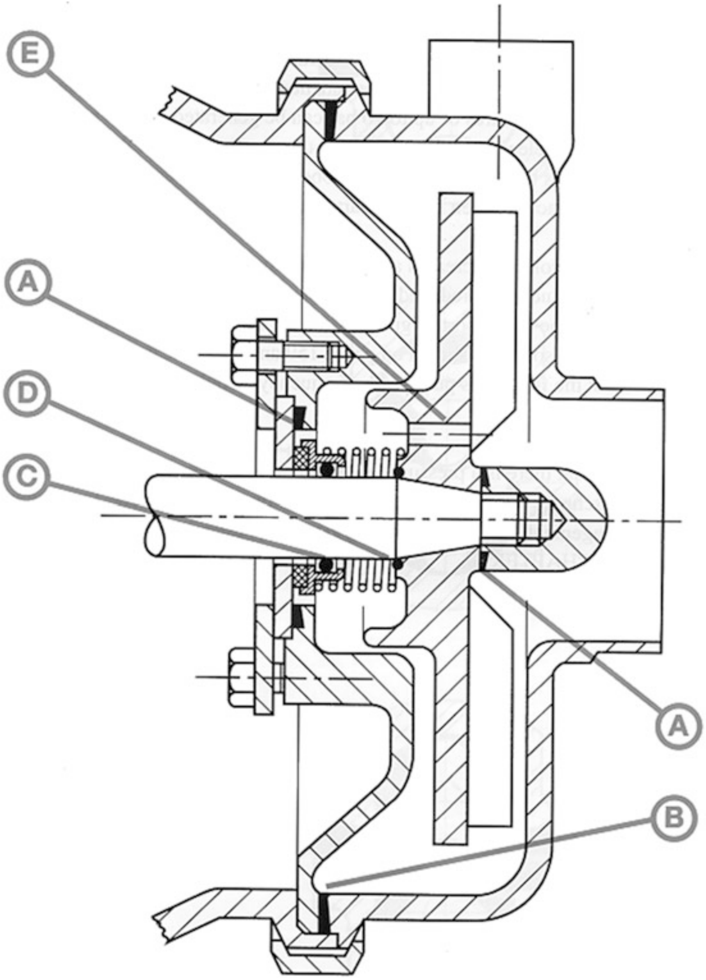


Fig. 4.10 Centrifugal pump—suggested design improvements

Table 4.8 Comparison of centrifugal pump designs

Unsatisfactory design, Fig. 4.9		Satisfactory design, Fig. 4.10	
Symbol	Description of feature	Symbol	Description of feature
(A)	These metal–metal joints may permit the ingress and retention of product and microorganisms	(A)	This metal–metal joint has been eliminated by means of a controlled-compression gasket
		(D)	This metal–metal joint has been eliminated by fitting a hygienic o-ring seal
(B)	Product residues may be retained in this crevice if cleaning-in-place is employed	(B)	Cleanability is improved by radiusing the corner and moving the gasket away from the corner
(C)	Product residues may be retained in this annular space after cleaning	(C)	The radial gap is increased to improve cleanability of the annular space
(D)	These areas experience low flow and the surrounding surfaces may not be properly cleaned if clean-in-place techniques are employed	(E)	The flow of liquid behind the impeller is increased to improve cleanability of the surfaces by placing holes in the shroud

4.5.2.1 Steel Pipe

Most pipelines are constructed of stainless steels; types 304 and 316 are the most widely used materials. As specified in ISO 2037: 1992 (E) and BS 4825: Part 1: 1991, the internal surface finish should be less than 1.0 µm R_a. This can be achieved with descaled or bright-annealed finishes without the need for mechanical polishing. Tube is manufactured in either seamless or welded form. While the former is highly regarded for its high quality, the latter is now widely used as it is satisfactory for most applications and less expensive than seamless tube. It is essential, however, that there should be full penetration of the weld, which should be smooth and flush with the interior of the pipe.

Stainless steel tubing is available with outside diameters ranging from 25.0 to 51.0 mm with a wall thickness of either 1.6 or 1.2 mm. It is most important that the internal diameters of pipe and fittings, including welded-type couplings, flanges, and gaskets, are properly matched as any abrupt changes in the bore can give rise to cleaning problems

4.5.2.2 Plastic Pipe

In certain applications, particularly those involving highly acidic products containing chlorides, plastic pipe is superior to steel pipe in terms of corrosion resistance. Plastic pipelines are also used for potable and ultrapure cold water. All plastics that come into contact with product must be approved for such use in the country concerned. Where there are no national standards, the plastic should comply with the internationally recognized standards such as the American Food and Drug Administration (USFDA) or the German Bundesgesundheitsamt (BGA). The material should naturally be compatible with any cleaning fluids used.

The plastics most commonly used in food-industry applications are polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS), and polypropylene (PP). The operating temperature ranges for these materials are PVC (5–60 °C), ABS (−40 to 80 °C), and PP (−20 to 90 °C). The maximum operating pressure depends on the temperature and the wall thickness. Plastic pipes are lighter and cheaper than their steel counterparts and their surface finish is superior. However, plastic pipework requires more frequent support to prevent sagging, which may offset any possible cost advantages.

Flexible tubing for food-industry use is available in PVC, ethylene vinyl acetate (EVA), low-density polyethylene (LDPE), and polytetrafluoroethylene (PTFE), among other materials. Most have a maximum operating temperature of between 60 and 70 °C, but PTFE is suitable for continuous use at temperatures in excess of 200 °C. Flexible tubing is available in reinforced or unreinforced forms with smooth or convoluted bores. The latter are more flexible but may experience cleaning problems.

Rubber (natural as well as synthetic) hoses are used in the dairy and brewing industries to fill or empty road tankers. The rubber must be approved for food-industry use and be compatible with the chemicals employed for cleaning and disinfection. Regular inspection of hoses is necessary as rubber deteriorates more rapidly than many materials.

4.5.2.3 Connections

There are two basic methods of joining lengths of pipework. Orbital welding is frequently used in large semipermanent installations. The process is automatic and, if properly executed, is capable of producing consistent, high-quality welds that do not require polishing.

Couplings are used when welding is impractical as, for example, when frequent dismantling and reassembly are required. A large number of different types of coupling are available, which are made to international and national standards as well as to equipment manufacturers' proprietary designs. Most types are available in versions that can be butt welded to the end of the pipe or attached by means of an expanded-type fitting. When using a welded coupling, care should be taken to ensure that the inside diameter of the fitting is the same as that of the tube and that the welded parts are constructed from the same grade of steel.

Table 4.9 summarizes the principal types of stainless steel coupling employed in the food industry, together with their main features. Several of these are illustrated in Fig. 4.11. The following features are required of a hygienic coupling. First is an absence of metal–metal joints, which can permit the ingress of microorganisms. Secondly, where gaskets are employed, care should be taken to ensure that they do not protrude into the bore of the tube as this will result in cleaning problems. This is best avoided by the use of customized gaskets and controlled compression. Finally, designs that feature internal crevices, which may harbor food residue and microorganisms, are also unsuitable.

Timperley (1997) also describes a variety of couplings for rigid plastic pipework. These are frequently of plastic construction, which are "welded" to the pipes. Solvent welding is normally used for ABS and PVC pipe and fusion welding for PP pipe. Flanged couplings are also employed; these normally feature galvanized steel backing plates to effect rigidity. The principal problem associated with both types of connection is the presence of internal crevices. However, these can normally be eliminated by good design. A typical example is illustrated in Fig. 4.12, where (A) is a customized gasket, which, when properly installed, is flush with the pipe bore.

Connections between flexible plastic hoses and stainless steel pipes were also discussed by Timperley (1997). These are of particular importance as flexible hoses often have to be used on filling machines and may therefore be a critical point. Such connections are often made by pushing the hose over the pipe stub and securing it with a single worm-drive hose clip. This is unsatisfactory as it results in a potential product trap. This problem is overcome using the arrangement shown in Fig. 4.13.

Flexible plastic hoses may be supplied with hygienic end fittings. With some designs, there may be abrupt changes in the internal diameter, which could result in cleaning problems with viscous products. If convoluted hose is employed, product may be retained after cleaning.

4.5.2.4 Installation of Pipelines

Pipelines should be installed in such a manner as to ensure self-draining. To achieve this, the following guidelines should be followed:

1. Pipelines must be adequately supported to prevent sagging and the resulting retention of residual liquid after draining. In practice, straight runs of stainless steel piping require supports at approximately 3 m intervals. Supports should also be installed either side of valves and at each change in direction. Pipelines should not be rigidly clamped, as this would prevent thermal expansion, thereby causing distortion.

   Plastic pipe is much less rigid than stainless steel pipe and therefore requires supporting at more frequent intervals. The coefficient of thermal expansion of most plastics is significantly higher than that of stainless steel. As a result, special attention must be given to the design and layout of plastic pipelines, with due provision being made for expansion loops. Pipes may be supported from the wall, the ceiling, or the floor. Supports should be of good hygienic design to minimize dirt and dust traps (see, e.g., Moerman 2011).
2. Pipelines should be installed so as to give a fall of about 1 in 100 if possible, to drain at the lowest point of the system. Where there is a restriction in a horizontal pipeline due, for example, to a flowmeter, the pipework on both sides of the restriction should fall to drain.

Table 4.9 Features of stainless steel pipework connections

Coupling type	Relevant standards	Comments
IDF-type coupling—welded	ISO 2852: 1993 BS 4825: Part 4: 1991 IDF Standard 14, 1960	Intended primarily for applications involving in-place cleaning. Overtightening can result of the protrusion of the gasket into the bore. The trapezoidal thread makes these couplings unsuitable for applications involving frequent dismantling
IDF-type coupling—expanded	ISO 2852: 1993 BS 4825: Part 4: 1991 IDF Standard 14, 1960	Protrusion of the gasket may result in the retention of food residues after cleaning
Clamp-type coupling	ISO 2852: 1993 BS 4825: Part 4: 1991 IDF Standard, 1960	Suitable for applications involving in-place cleaning where frequent dismantling is necessary. Welded and expanded versions are available. The welded version is preferable for handling viscous products
SMS coupling	SMS 1145, 1957	The standard describes four screwed-type expanded couplings. All feature rounded screw threads, which make them suitable for frequent dismantling. Only one version is considered suitable for handling viscous products and for in-place cleaning. The others have an internal annular crevice
DS coupling	DS 722, 1955	Similar to one version of the SMS coupling. An annular crevice between the ends of the tubes and the bore of the gasket may retain product. Suitable for frequent dismantling
DIN coupling	DIN 11851, 1989	Expanded-type screwed coupling. Undesirable features include an internal annular crevice and metal–metal joints resulting in possible retention of product and microorganisms. An alternative design eliminates these problems. Suitable for frequent dismantling as threads are rounded
RJT (ring joint type) coupling	BS 4825: Part 5: 1991	Both welded and expanding versions are available. Easily dismantled. An internal annular crevice makes it unsuitable for in-place cleaning
3-A coupling—ground seat type	US 3-A Sanitary Standard 08-17 Rev, 1976	Expanded-type coupling. A conical metal-to-metal seat often requires a high wrench torque to effect a seal. The seat, together with an internal annular crevice, makes it unsuitable for in-place cleaning. A similar fitting, described in BS 3581:1963, has now been withdrawn
3-A coupling—gasket seat type	US 3-A Sanitary Standard 08-17 Rev, 1976	Gasket seat screwed coupling. When correctly assembled, a smooth crevice-free internal surface is obtained. Suitable for handling most products and for in-place cleaning
Flanged joints	–	Joints without gaskets are unhygienic (metal–metal joints); discontinuities in bore due to misalignment. An improved design features a gasket and spigot–recess arrangement to ensure alignment and controlled gasket compression. Suitable for in-place cleaning

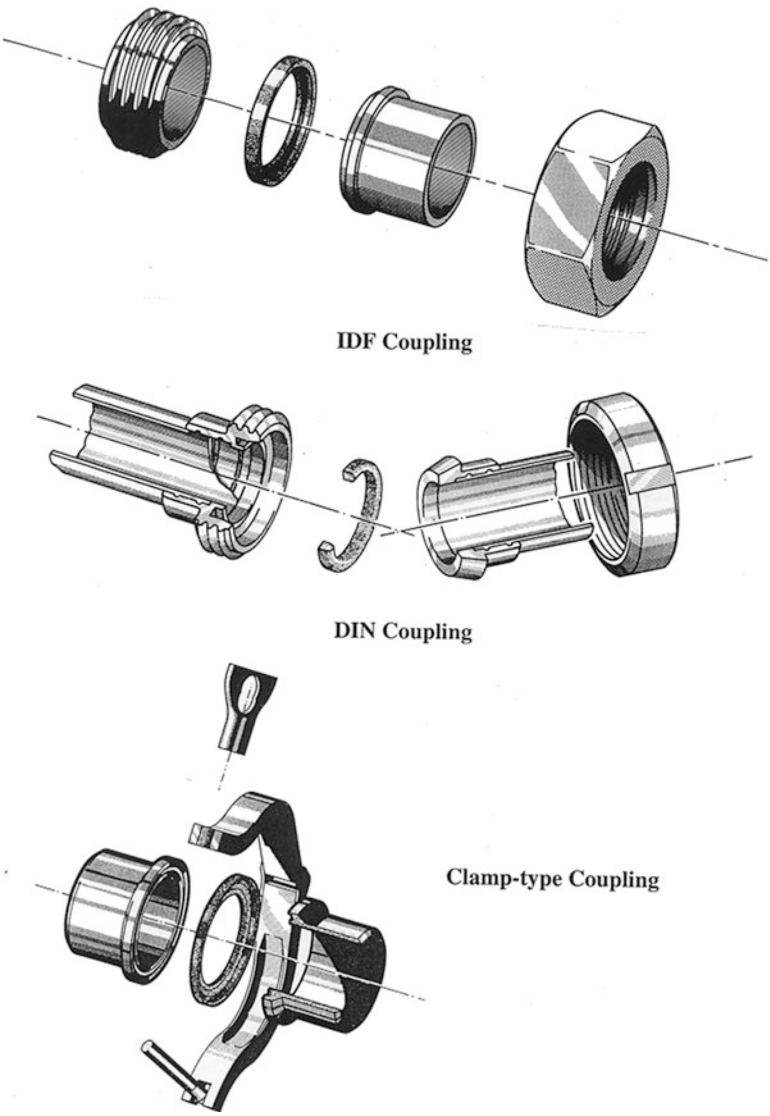


Fig. 4.11 Examples of pipe couplings

3. Changes in pipe diameter should be made as smoothly as possible as abrupt changes may give rise to cleaning and drainage problems. The blanking piece shown in Fig. 4.14a, for example, is unsatisfactory, for two reasons. Firstly, residual liquid will be retained in (A) when the flow to drain is in the direction shown. Secondly, product can be retained at (B). The concentric reducer shown in (b) cannot be drained either; liquid is again retained at (A). Eccentric reducers, Fig. 4.14c, are satisfactory in this respect and should be used.
4. Blanked-off tees and other dead-legs should be avoided wherever possible, as they constitute a potential hazard. This is discussed further below.
5. Undrainable sections can result when a level change of horizontal pipe is necessary to avoid obstructions—see Fig. 4.15a. A drainable arrangement is shown in Fig. 4.15b.

Fig. 4.12 Hygienic plastic pipe coupling

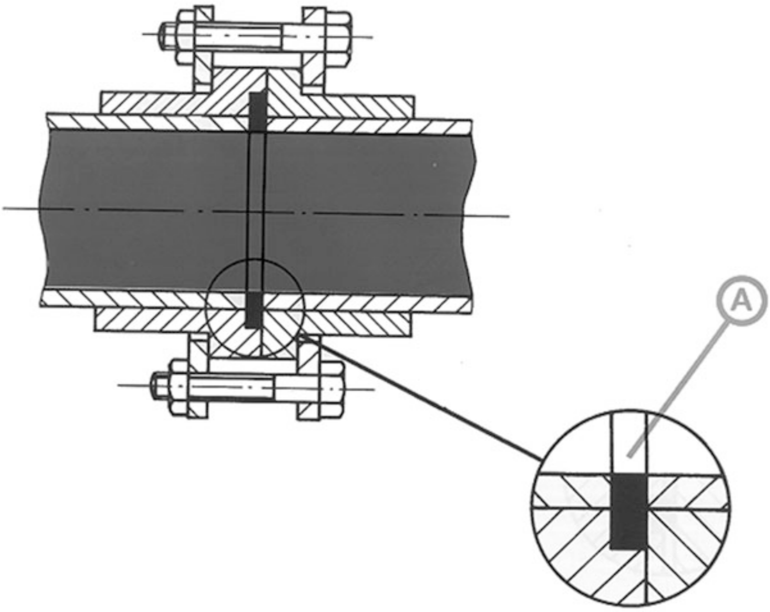


Fig. 4.13 Hygienic hose connection

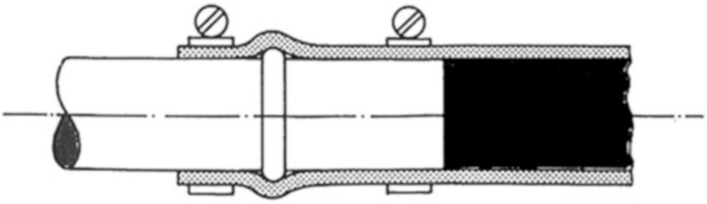
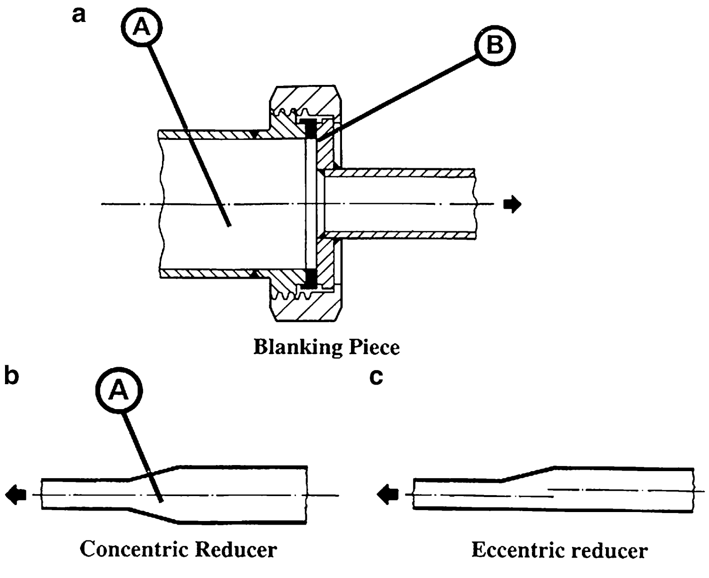


Fig. 4.14 Examples of satisfactory and unsatisfactory reducer



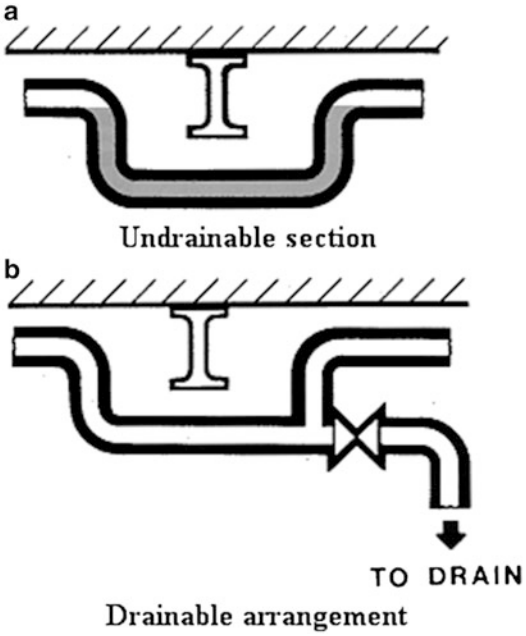


Fig. 4.15 Satisfactory and unsatisfactory pipe drainage arrangements

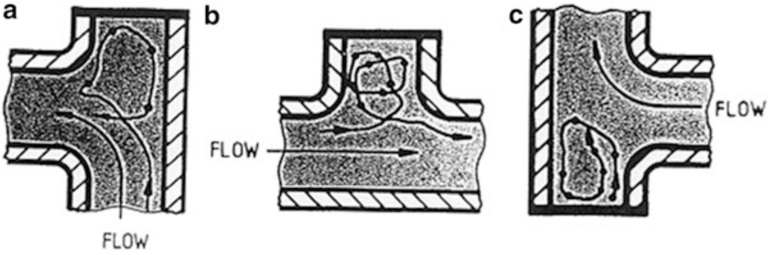


Fig. 4.16 Flow visualization within "dead-legs"

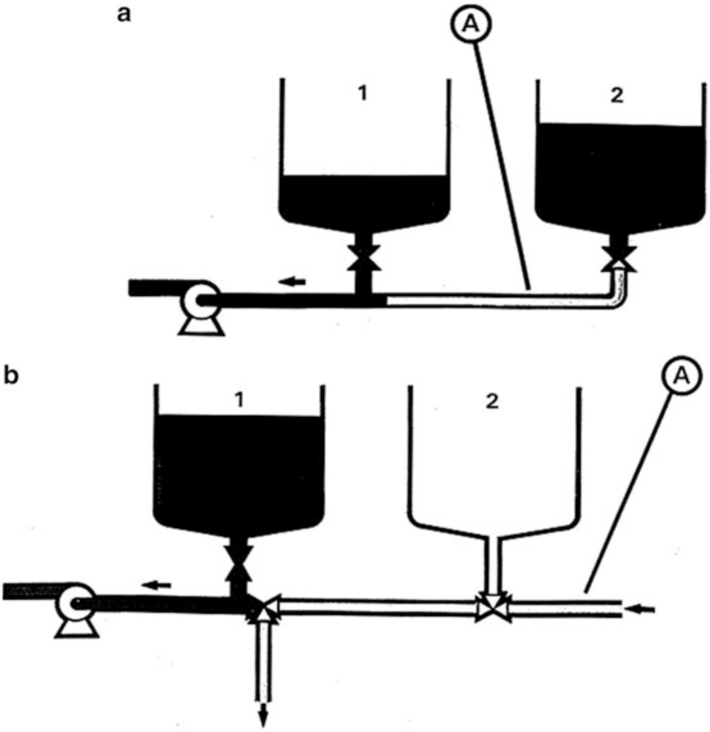
4.5.2.5 Dead-Legs

As noted above, dead-legs should be avoided whenever possible. Where their use is absolutely necessary, as, for example, to mount sensors, they should be designed to be self-draining and to facilitate effective cleaning. Typical examples of tees, each of which has the same dimensions, are shown in Fig. 4.16. That shown in (a) is satisfactory. The branch is self-draining and, as the fluid is directed into the branch at a relatively high velocity, cleaning is satisfactory. In (b), the flow is across the dead-leg. This results in lower flows and hence less satisfactory cleaning. Flow away from the dead-leg, as in (c), results in even poorer cleaning.

Another cause of dead-legs is faulty design or installation of plant. Consider, for example, the two feed vessels shown in Fig. 4.17a. These share a common discharge line and are in continuous use for lengthy periods of time. A typical production cycle could be as follows:

1. Vessel 2 acts as the feed tank while vessel 1 is being filled.
2. Vessel 1 then acts as the feed tank while vessel 2 is being filled, and so on.

Fig. 4.17 Satisfactory and unsatisfactory tank outlet arrangements



Stagnant product remains in line (A) between the vessels while vessel 2 is being refilled. Depending on the product, its temperature, and the time, this arrangement may give rise to microbiological and perhaps cleaning problems. A better arrangement is shown in Fig. 4.17b. This permits the line between the vessels to be given an intermediate rinse of potable water at (A). This arrangement also prevents the line from being backfilled should the feed be taken from vessel 1 first. Special precautions are, however, required to prevent contamination if detergent rather than potable water is used as the intermediate rinse.

4.5.2.6 Air Pockets

Care should be taken to avoid air pockets in pipework, as these will create cleaning problems. Examples of where they may occur include the branch of a blanked-off tee pointing vertically upwards and in the raised section of a horizontal run of pipe routed vertically upwards and then downwards to avoid beams, doorways, and other obstructions.

4.5.2.7 Pipework Insulation

Insulation used in food-production areas must be nontoxic, resistant to moisture when applied to cold pipes, and must not support mold growth. If necessary, the bare pipework should be coated with a protective paint to prevent stress corrosion. The insulation should be sealed with a nontoxic, mildew-resistant coating, which should provide a vapor barrier in areas of high humidity. A suitable cladding (aluminum, stainless steel, or glass-reinforced plastic) should be used to protect pipework liable to mechanical damage.

4.5.3 Valves

Valves are widely used in the food and drinks industry to control liquid flow. They fulfill a variety of roles: shut off, diversion, pressure and flow regulation, pressure relief, and non-return. As with many other plant items employed in the food industry, types 304 and 316 stainless steels are widely used as construction materials. While there are no standards for the surface finish of valve components that come into direct contact with product, this is normally specified as being less than 1 μm R_a.

Table 4.10 summarizes the principal types of on/off and diversion valves commonly used in the food industry. The selection of an appropriate valve for a given duty depends on several factors. For example:

1. Is the envisaged application aseptic or hygienic?
2. Is diversion as well as on/off capability required?
3. Is automated or remote operation required?
4. What are the physical and chemical characteristics of the product? Does it contain solids?
5. Cost implications?
6. Are frequent inspection and/or maintenance likely to be a problem?

Figure 4.18 illustrates several of the types of valve listed in the table.

Where cleaning-in-place is planned, a single valve seat must never be relied upon to protect the product from the cleaning fluid even if the product is to be maintained at a higher pressure. In such circumstances, two valves with the space between them open to the atmosphere may be used. However, this arrangement has largely been superseded by the introduction of double-seat, mix-proof, or block-and-bleed-type valves. Figure 4.19 illustrates, by way of example, a mix-proof linear plug and stem valve in the closed (top) and open (bottom) positions. The valve has a space (A) between the two seats so that, if either fails, the fluid will leak to drain through the bore of the lower valve stem (B). Each valve head is held independently on its seat by spring pressure. On opening, the lower valve head is raised off its seat first and moves upwards a short distance before contacting the upper valve head. Both then move together into the open position, as shown.

As noted above, valves also perform other functions in food-manufacturing plants. The flow-control valve, for instance, as its name implies, regulates the flow rate of product through the pipeline. It is similar in construction to an on/off linear plug and stem valve but has a tapered valve head. The valve may be controlled manually but, more frequently, this is done automatically and remotely with the aid of a pneumatic actuator. As is the case with the on/off and diversion types, its suitability for hygienic or aseptic applications is determined by the design of the valve stem seal.

In certain process operations, such as the continuous mixing of aerated products, it is necessary to maintain a constant back pressure. This is achieved by means of a back pressure valve, which may be of the membrane or diaphragm type. The former is suitable for hygienic and aseptic applications.

Pressure relief valves are fitted in food-processing systems to ensure that unforeseen increases in pressure do not create a safety hazard or damage equipment. Most are variants of the on/off linear plug and stem valve fitted with a spring having a much lower rating, which can be varied to suit the requirements. Care should be taken when mounting this type of valve to avoid hygiene problems. A 4-port version of this valve is commonly used to protect equipment on the downstream side of a positive displacement pump from overpressure.

Finally, non-return valves are used to ensure that liquid flows in one direction only. When the flow is in the desired direction, the drag causes the valve head to move away from its seat. When the flow stops, a lightly loaded spring returns the valve head to the seat, thereby preventing flow in the reverse direction. Such valves are unsuitable for use with viscous liquids and, because of the nature of their design, there could be cleaning problems.

Table 4.10 Characteristics of on/off and diversion valves

Valve type	Description	Hygienic characteristics
Plug cock valve	Plug cock consists of a conical plug having either a straight-through port (on/off) or ports arranged in a tee configuration (three-way), which is rotated in the tapered bore of the body	Valve cannot be cleaned in place as product is trapped between plug and bore
Ball valve	Similar to the plug cock valve but the plug is replaced by a sphere (ball). On/off operation only. Not easily dismantled for cleaning. Steam-purged version available	Valve cannot be cleaned in place if it is left fully open after use due to product entrapment. It may be cleanable in place if left in the half-open position—this should be carefully checked, however
Butterfly valve	Comprises a disc, which is rotated through 90° within the valve body. A rubber seal clamped between the halves of the body provides a seat for the disc to close on and a disc spindle seal. On/off operation only	Incorporates most of the features required for hygienic applications. Can be cleaned in place. Buildup of product on the edge of the disc may occur and cause a cleaning problem
Linear plug and stem valve	Based on the globe valve. The flow is controlled by a valve head fitted with either a rubber or PTFE seal. Various types of stem seal, including a lip, an "o" ring, a diaphragm, a bellows, and a steam barrier. Manual or automated operation. Designs are available for on/off and diversion applications	The following stem seal arrangements are suitable for hygienic operation only: lip seal and "o" ring. Diaphragm seals and bellow seals are suitable for aseptic applications. The steam barrier is not widely used because of its high cost
Diaphragm valve	The diaphragm is clamped between the valve bonnet and body and is pressed against the weir by an external mechanism. The diaphragm is subject to wear and must be replaced regularly. A flow-diversion variant is available	This valve is of simple design and glandless, which makes it suitable for both hygienic and aseptic applications
Membrane valve	A rubber hyperboloid membrane clamped between the linear valve plug, the valve head, and body to provide crevice-free and bacteria-tight joints. The diaphragm is subject to wear and should be replaced at regular intervals. Two on/off valves can be combined to form a diversion valve	The valve is suitable for both hygienic and aseptic applications
Rising stem tank outlet valve	This is a modified version of the on/off linear plug and stem valve. It is usually fitted with a flange incorporating the valve seat, which is welded into the base of the tank. In the open position, the valve head projects into the vessel	This type of valve is widely employed for hygienic and, where necessary, aseptic applications
Falling stem tank outlet valve	Similar to rising stem valve. However, in this design, the valve head drops down from its seat. It may be used where the agitator blades are in close proximity to the bottom of the tank	Versions are available for both hygienic and aseptic applications

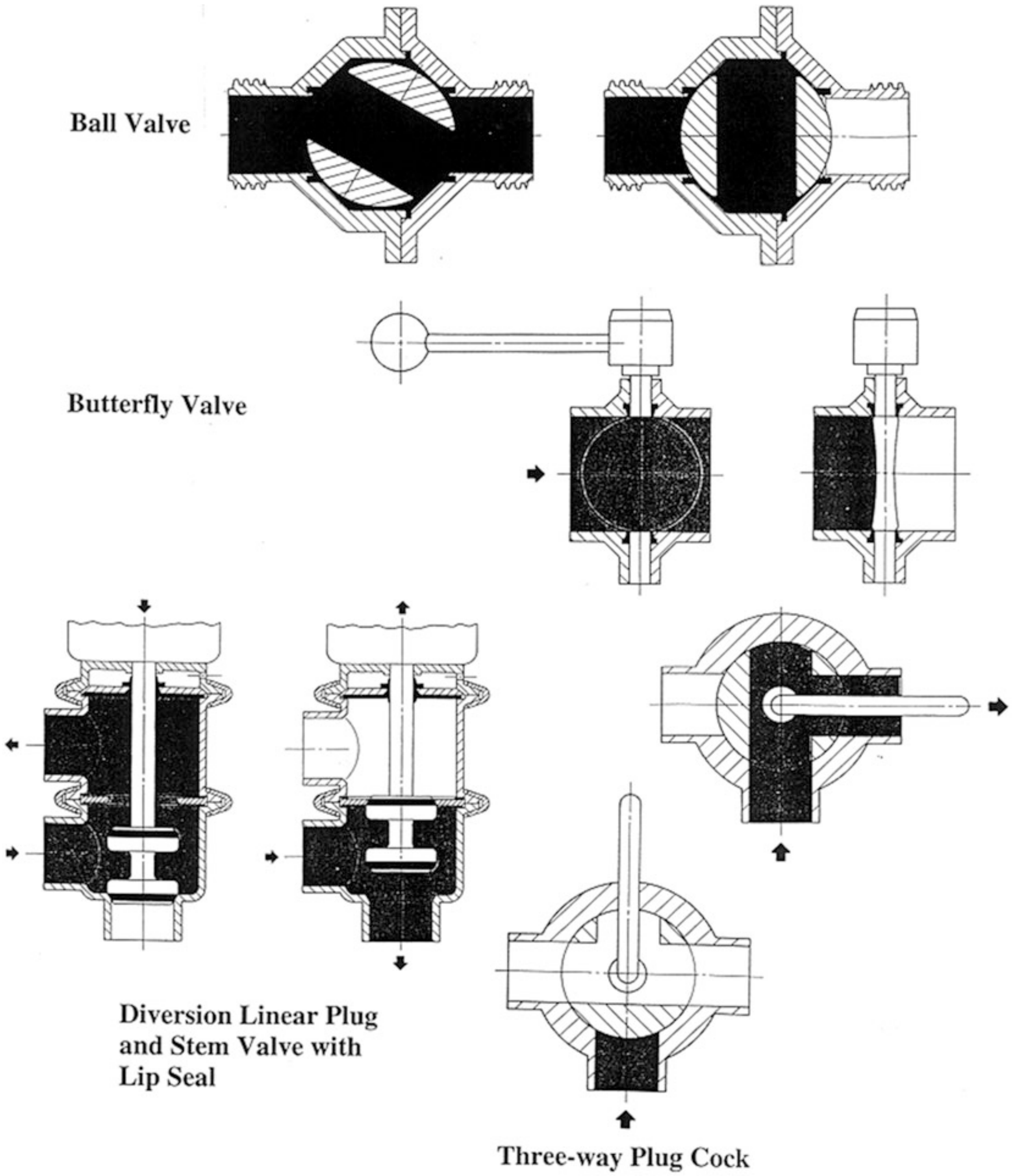


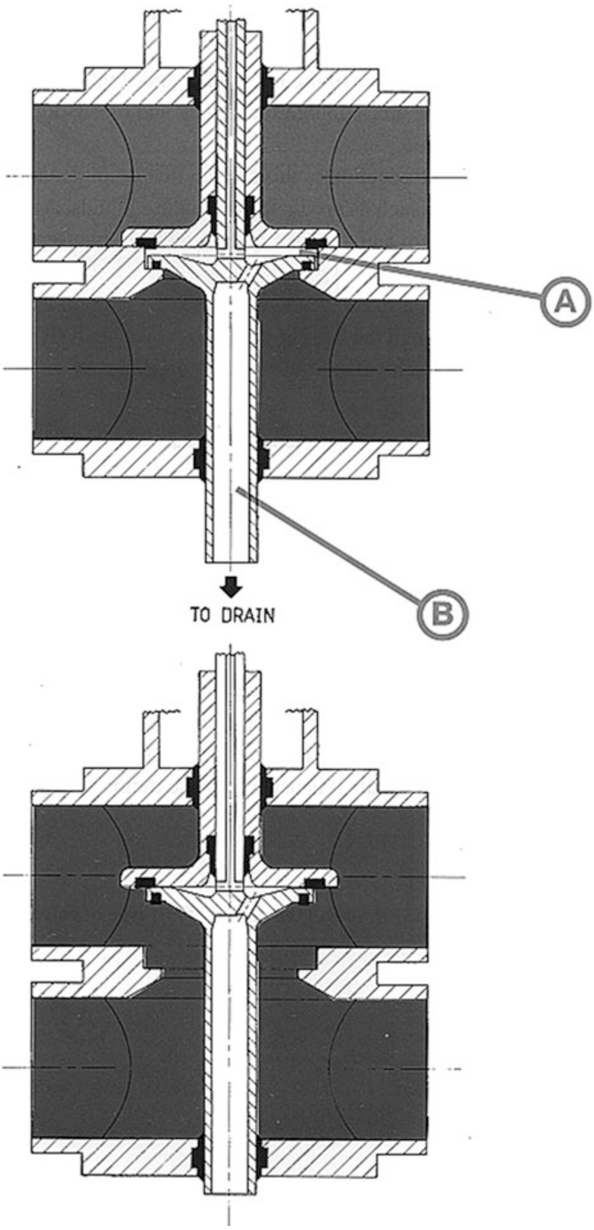
Fig. 4.18 Examples of on/off and diversion valves

4.5.4 *Post-process Can Handling*

Hygiene problems are not restricted to liquid food products; solid foods are equally vulnerable. Some of these potential problems are described in this and the following section.

Thorpe and Barker (1985) describe how good hygienic design can significantly reduce the occurrence of infection of canned food resulting from temporary leakage through damaged can seams. They made the following points relating to leaker infection:

Fig. 4.19 Mix-proof linear plug and stem valve



1. Leaker infection is the commonest form of spoilage encountered in the canning industry.
2. Leaker infection has been associated with a number of serious food-poisoning incidents.
3. Manual unloading of wet processed cans greatly increases the risk of infection by food-poisoning organisms.
4. Abuse of can seams on conveying equipment can result in temporary leaks through the seams.
5. Wet cans may become infected while being conveyed over contaminated can-handling equipment surfaces.
6. The risk of infection through temporary leaks disappears once cans and their seam regions are dry.
7. Carry-over of chlorinated cooling water onto runway surfaces does not prevent the growth of bacteria.

8. Can drying reduces the time cans are vulnerable to leaker infection and the surface area of can-handling equipment that becomes wet during production.
9. Badly designed, constructed, and maintained equipment is much more difficult to clean efficiently, and this, in turn, reduces the effectiveness of subsequent disinfection treatments.

In short, the lessons to be learnt from the above are (a) avoid manual handling of wet cans (batch retorts should always be unloaded mechanically), (b) avoid rough handling of the cans, (c) minimize contact between the seams and standing water on equipment surfaces, and (d) use a can dryer. There are two basic causes of can damage. Impact abuse occurs when cans roll or slide down runways and knock into each other or protruding sections of the conveyor. It can occur when cans are slowed down or caused to change direction. Pressure abuse normally occurs when cans on cable conveyors stop moving forward but the cable itself continues to run. As a result, cans ride up on each other so that the seam of one can presses into the body of the next can.

Water deposited on can-handling systems from the cans themselves not only makes it possible for bacteria to multiply on equipment surfaces but also provides the primary means of transferring bacteria onto cans. The chances of contamination greatly increase if the equipment surfaces have not been adequately cleaned and disinfected and if the can-handling systems have been badly designed, constructed, installed, or maintained. By way of example, Fig. 4.20 illustrates some of the problems that can occur with a push bar elevator:

(A) Can seams run on a solid backplate. Both seams are in contact with the plate and risk contamination. An improved design in which the plate is replaced by rails is shown in Fig. 4.21.
(B) There is double-seam contact with the push bars. An improved design is also shown in Fig. 4.21.
(C) The covering material on the retarding mechanism is usually soft and often porous. When it becomes heavily contaminated, bacteria are transferred onto the wet can bodies.
(D) Can transfer timing device. Unless there is a smooth transition from the turning wheel to the “pockets” between bars, the cans will be subjected to severe abuse.
(E) The buildup of cans approaching the elevator may cause impact abuse. This can be minimized by running the elevator at a slightly faster speed than the can line.
(F) The distance between the bottom of the side guards and the floor restricts access for general housekeeping. The minimum clearance should be 200 mm.

In view of the hygiene and can abuse problems with this type of elevator, Thorpe and Barker recommended that alternatives (e.g., magnetic elevators or alpines) be used.

Can seams may also be contaminated indirectly. In this process, bacteria are transferred from the surfaces of can-handling equipment onto the bodies of the cans. These are carried into the seam area in water droplets running down the cans. Thorpe and Barker (1985) cited a large number of cases where hygienic design is critical. These include, for example, the method of attaching rails to support framework; the method of joining side guides to those of straight conveyor sections, hinge links on slatted conveyors, can dryers, particularly those sited within hydrostatic sterilizers; and the loading and unloading of hydrostatic sterilizers. These and other relevant topics are treated in great detail and the reader is referred to this report for further guidance.

4.5.5 Product Transfer Systems

Campden Technical Manual No. 7 (CCFRA 1983) addresses the hygienic design of fruit and vegetable preparation lines and, in particular, problems associated with the product transfer systems. In this report, the Working Party noted that, whereas large or expensive plant items were subjected to considerable scrutiny, the hygienic design of product transfer systems (hoppers, conveyors,

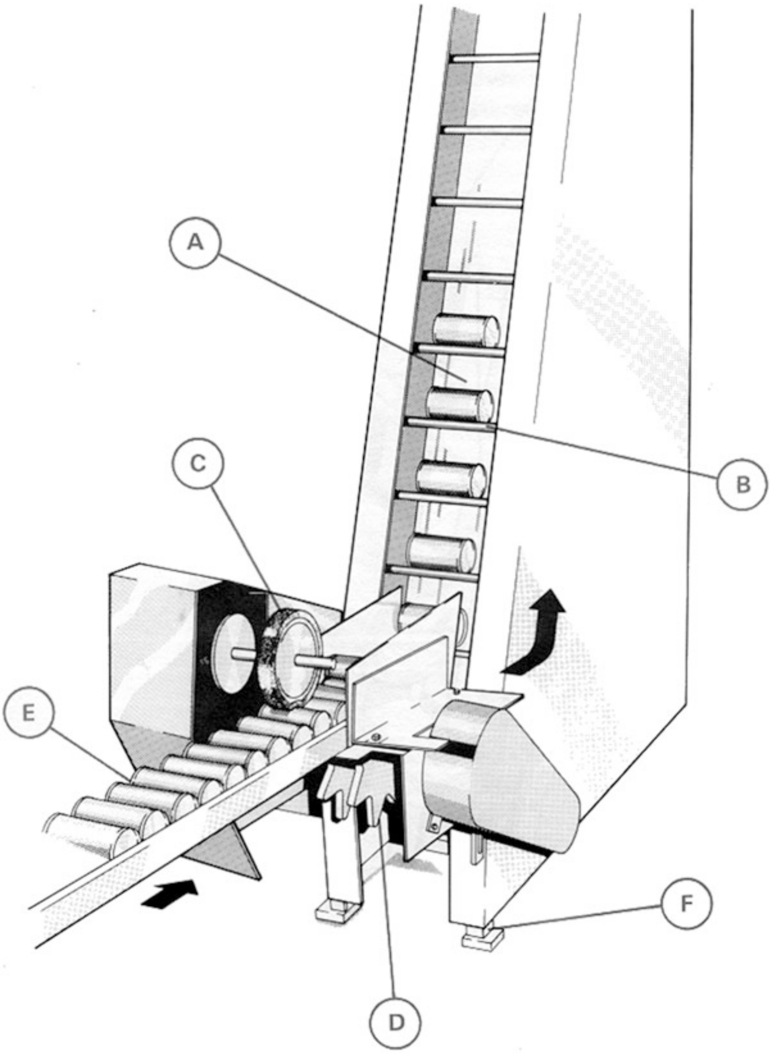


Fig. 4.20 Hygiene problems associated with a push bar elevator

elevators, etc.) often received little attention. They attributed this to a number of factors including the pressure of tight deadlines, the fact that the equipment is often used to meet the particular and frequently short-term needs of different production lines, and local design and construction by nonspecialist suppliers. As a result, a number of recurrent faults, which tended to be repeated at different points on the line, were observed. These were:

1. Incorrect location of adjoining equipment, which results in inefficient discharge of product from one unit to the next. For example, the end of a conveyor belt should be positioned directly over a reception hopper to ensure that the product transfer is effected smoothly and without spillage. The use of a deflector plate as an alternative to correct design and location is a poor example of hygienic design.
2. Design faults that permit product to become trapped in a "backwater" can result in loss of product quality, microbial growth, and product contamination. In addition, they increase the time and cost of cleaning programs. There are numerous examples. The use of deflector plates, behind which product can accumulate, is one common example. The inadequate design of hoppers that results in product retention within them is another. A third is the poor design of conveyor rollers, which allows debris to lodge in their ends.

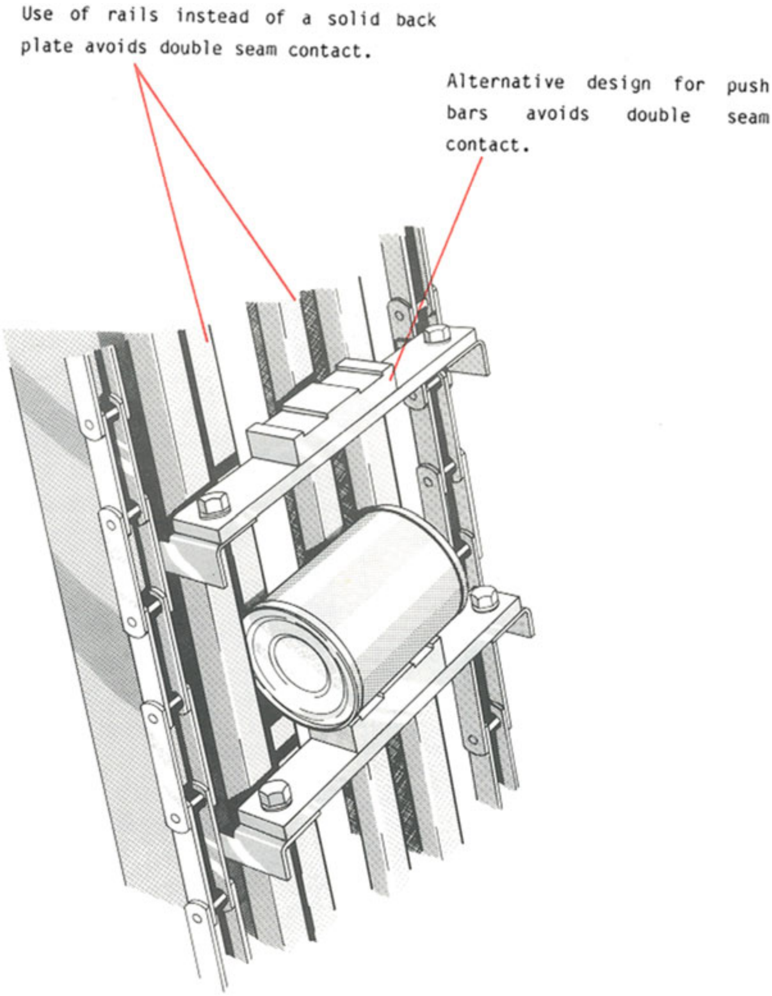


Fig. 4.21 Suggested improvements to push bar elevator

3. The use of unsuitable fasteners, which may work loose and cause damage to other equipment and give rise to consumer complaints. As discussed in Sect. 4.4.3, they may also cause hygiene problems.

The authors cite a large number of examples of poor hygienic design and propose solutions to alleviate the resulting problems. Two examples are reproduced here. Figure 4.22 illustrates an unsatisfactory design for the transfer of product from a conveyor to an inspection belt. The backstrip (A) serves no useful purpose. Moreover, debris from the belt collects on the back of the strip and provides a source of nutrients for the growth of microbial slime on surfaces. The height of the conveyor (B) is inadequate and prevents its correct location with respect to the inspection belt. This creates a number of problems. As the full width of the inspection belt is not utilized, the depth of product is too great to permit adequate inspection. Moreover, debris builds up on the inspection belt frame beneath the conveyor and behind the product guide and spills onto the floor (C). Product tends to flow in surges from the conveyor, thereby causing "waves" to pass down the inspection belt. This, in turn, results in product being pushed high up the side of the guide, which tends to become trapped until subsequent surges sweep it back into the main flow. Another design fault is that the flat horizontal frame members provide a surface on which debris can lodge. These sections should be replaced by tubular-section material or square-section members turned through 45° to provide sloping surfaces. The authors conclude that these problems could be overcome by replacing the existing conveyor belt with a suitable vibrator conveyor.

Fig. 4.22 Unsatisfactory product transfer

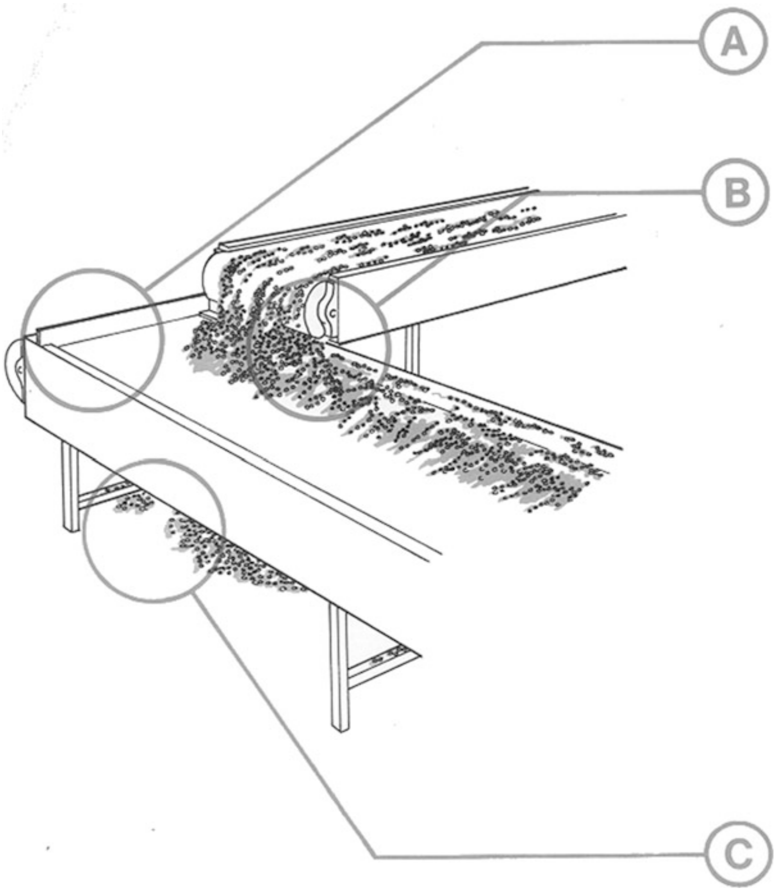


Figure 4.23 illustrates several design faults associated with a raised walkway. The principal hygiene problem here is that dirt may be transferred from clothing or footwear onto the product line beneath the catwalk (A). The problem is compounded by the use of expanded metal or mesh flooring (B) through which extraneous matter can pass. Finally, open risers above the level of the product (C) can result in dirt being kicked into it. An improved design is shown in Fig. 4.24. Here, the decking (A) is constructed from solid plate. Checker plate is particularly suitable for this purpose as it features a raised anti-slip surface. Fitting a kickplate (B) minimizes the chance of dirt being transferred from footwear. Where possible, the decking and kickplates should be of one-piece construction. Finally, the risers are constructed of the same anti-slip plate as the decking. Those above the level of the product flow are encased (C) to prevent it from being contaminated by dirt.

4.6 Closure

This chapter has presented an overview of the hygienic design of food-processing equipment. The subject is complex and multifaceted. It involves interactions between process factors, materials of construction, and the detailed mechanical design. It is clearly impossible to cover all aspects hygienic design in the depth they deserve; the reader should therefore refer to the references cited for more detailed guidance.

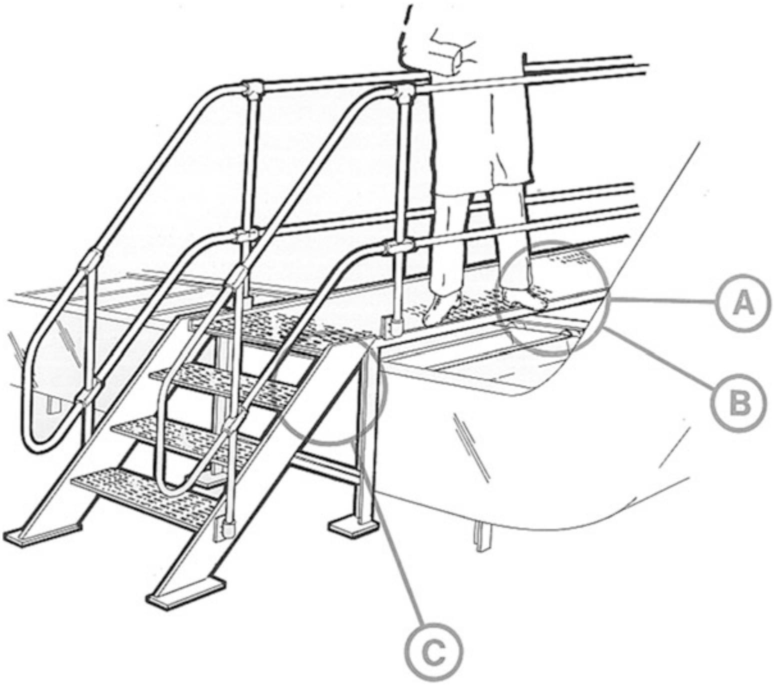


Fig. 4.23 Unsatisfactory walkway

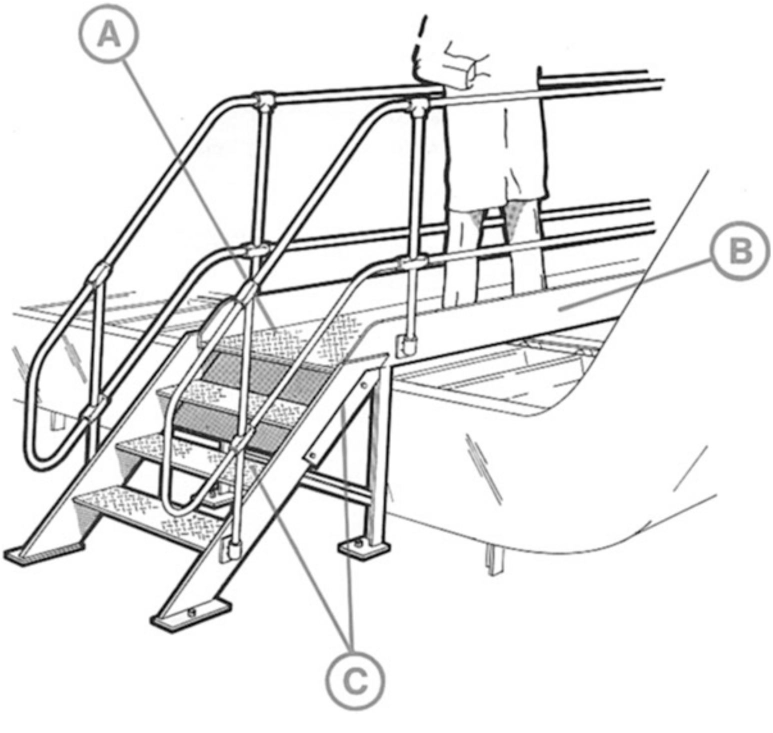


Fig. 4.24 Satisfactory walkway

References

Brougham, P. (2011) "Design, installation and operating of cleaning and disinfectant chemical storage, distribution and application systems in food factories", Chapter 28 in "Hygienic design of food factories", (eds) Holah, J. and Lelieveld, H. L. M., Woodhead, Cambridge, England.

BSI (2005) "Stainless steels. Technical delivery conditions for sheet/plate and strip for general purposes", British Standard BS EN 10088–2, British Standards Institution, London.

BSSA (2010) "Specifying finishes for stainless steel flat products (sheet and plate)", British Stainless Steel Association, Sheffield, England, www.bssa.org.uk/topics.php?article=47.

CCFRA (1992) "The principles of design for hygienic food processing machinery", Technical Memorandum No. 289, prepared by the Hygienic Design Working Party, Campden Food & Drink Research Association (now Campden BRI), Chipping Campden, Gloucestershire GL55 6LD, England. Reprinted 1992.

CCFRA (1983) "Hygienic design of food processing equipment", Technical Manual No. 7, prepared by the Working Party on Hygienic Design of the Heat Preserved Foods Panel, Campden Food & Drink Research Association (now Campden BRI), Chipping Campden, Gloucestershire GL55 6LD, England. Reprinted 1992.

EC (2004) Regulation (EC) No. 1935/2004 of the European Parliament and of the Council on materials and articles intended to come into contact with food and repealing Directives 80/590/EEC and 89/109/EEC, 27 October, 2004, Available online at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2004:338:0004:0017:en:PDF.

FDF/FMA (1967) "Hygienic design of food plant", Joint Technical Committee, Food & Drink Federation/Food Manufacturers Association, London.

Foresythe, S.J. and Hayes, P. R. (2000) "Food hygiene, microbiology and HACCP", 3rd edit., Aspen, Gaitersburg, MD.

Fraser, I. (2010) (ed.) Guide to the application of the Machinery Directive 2006/42/EC, 2nd edit., European Commission Enterprise and Industry, June, 404 pp. Available online at http://ec.europa.eu/enterprise/sectors/mechanical/files/machinery/guide-appl-2006-42-ec-2nd-201006_en.pdf.

Green, D.W and Perry, R.H. (2008)(eds) "Perry's chemical engineers' handbook", 8th edit., McGraw-Hill, New York, Section 25.

ICMSF (1988) "Microorganisms in foods 4 – Application of the Hazard Analysis Critical Control Point (HACCP) system to ensure microbiological safety and quality", International Commission on Microbiological Specifications for Foods, Blackwell Scientific, Oxford.

Jowitt, R. (1980) (ed.) "Hygienic design and operation of food plant", Ellis Horwood, Chichester, pp. 241–285.

Katsuyama, A.M. and Strachan, J.P. (1980) (eds) "Principles of food processing sanitation", The Food Processors Institute, Washington, DC.

Lilieveld, H.L.M., Mostert, M.A. and Curiel, G.L. (2003) "Hygienic equipment design", Chapter 8 in "Hygiene in food processing", (eds) Lilieveld, H.L.M., Mostert, M.A., Holah, J. and White, B., Woodhead, Cambridge, England.

Machinery Regulations (1992) "The Supply of Machinery (Safety) Regulations 1992", Statutory Instrument No. 3073, HMSO, London. Available online at www.legislation.gov.uk/uksi/1992/3073/made. The 1992 Machinery Regulations were amended in 1994, 2005, 2008 and 2011; for details of the current version, see http://www.legislation.gov.uk/uksi/2011/2157/contents/made. For a guide to the application of the corresponding European Directive, see Fraser (2010).

Moerman, F. (2011) "Hygienic design of piping for food processing support systems in food factories", Chapter 21 in "Hygienic design of food factories" (eds) Holah, J. and Lelieveld, H. L. M., Woodhead, Cambridge, England.

Peters et al. (2003) "Plant design and economics for chemical engineers", 5th edit., (eds) Peters, M.S., Timmerhaus, K. D. and West R.E., McGraw-Hill, New York, 988 pp.

Ridgeway, G.R. and Coulthard, R. (1980) "Hygienic design of plant exterior" in "Hygienic design and operation of food plant", (ed). Jowitt, R., pp. 53–77, Ellis Horwood, Chichester.

Shapton, D.A and Shapton N.F. (1998) "Principles and practices for the safe processing of foods", Woodhead, Cambridge, 472 pp.

Thorpe, R.H. and Barker, P.M. (1985) "Hygienic design of post process can handling equipment", Technical Manual No. 8, Campden & Chorleywood Food Research Association (now Campden BRI), Chipping Campden, Gloucestershire GL55 6LD, England.

Timperley, A.W. (1997) "Hygienic design of liquid handling equipment for the food industry", Technical Manual No. 17, 2nd edit., Campden Food & Drink Research Association (now Campden BRI), Chipping Campden, Gloucestershire GL55 6LD, England.

Timperley, D.A. and Timperley A.W. (1993) "Hygienic design of meat slicing machines", Technical Memorandum No. 697, Campden Food & Drink Research Association (now Campden BRI), Chipping Campden, Gloucestershire GL55 6LD, England.

Chapter 5
Movement of Materials

R.C. Kill

5.1 Introduction

In its widest sense, a "conveyor" can be defined as any device designed to continuously transport packages or loose materials, either horizontally or at an inclination. Many types of conveyor are used in the food factory; the most widely used types are described in this chapter. Movement may be imparted by gravity, manually or by motive power. It may take place overhead, at working height, or at floor level.

Conveyors are designed to move either bulk material or unit loads; some systems will handle both. Bulk material consists of loose, unpackaged solids. Unit loads are groups of items that may be handled as a single entity, often on pallets. The salient features of each are described below.

5.1.1 Bulk Conveying

This encompasses the movement of loose, unpackaged material, which, although frequently dry and free-running, such as grain, may be wet, hot, or sticky. The principal factors influencing the correct selection of a bulk conveying method include movement specifications such as speed, frequency, and distance. However, knowledge of the properties of the material, including its flammability, condition, and susceptibility to infection, infestation, and the generation of dust, is also essential.

Commonly used types of bulk conveying system include flight conveyors, chain conveyors, vibrating conveyors, screw conveyors, bucket elevators, belt conveyors, and pneumatic conveyors. Major advantages accrue from using bulk handling in flour mills, bakeries, and biscuit factories, particularly the latter, which are generally equipped to receive bulk ingredients such as flour, sugar, fats, milk, glucose, syrup, and malt. Here bulk handling of flour and sugar is synonymous with pneumatic conveying.

R.C. Kill (✉)
Micron2 Ltd, Betton Mill, Betton Rd, Market Drayton, Shropshire TF9 1HH, UK
e-mail: ronkill@micron2.com

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_5,

5.1.2 Unit Loads

A unit load consists of a group of items or a mass of bulk material so arranged or restrained that it may be picked up or handled as a single unit until it is disassembled. The ability to handle such loads is a fundamental requirement in many food factories. Unit loads assume many forms, amongst which are commonly encountered:

1. Assemblies of packages on pallets, skids, sheets, etc.
2. Numbers of small items or masses of bulk materials in box pallets, bins, tanks, “semi-bulk” containers, etc.
3. Strapped, fastened, shrink-wrapped or other restrained or bundled assemblies
4. Loose loads handled as masses or single large containers (e.g., drums) handled by squeeze, baling, or drum clamps

Unit loads may be handled by conveyors, elevators, cranes and hoists, and by trucks of various types.

Properly applied, the concept of movement in unit loads standardized on the basis of weight, size, or number of items has many advantages compared with single-item handling. These advantages include faster and cheaper movement and stocktaking, better space utilization, reduced product damage, better stock rotation, and improved safety.

5.1.3 Pallets and Palletization

5.1.3.1 Pallets

A pallet consists essentially of a horizontal platform, which is used as a base for assembling, storing, handling, and moving unit loads, in particular. Pallets are available in a wide variety of designs. For example, they may have single or double faces (decks), be equipped with multiple access points for handling by forklift trucks, and be constructed from a variety of materials that may make them suitable for single- or multiple-trip use.

A pallet differs from a skid (or stillage) in respect of its ability to stack; it has a larger area on its lower surface to spread the load. This is particularly true of double-faced pallets, but even a single-faced pallet should have at least three bearers below its upper deck.

Pallets designed for handling by fork trucks are constructed with single or double decks from wood, plastics, steel, wood reinforced with steel, aluminum, or fiberboard. Plastic pallets are now a common requirement in food production areas for reasons of good hygiene. They are easily washed and are nonabsorbent. The under-clearance of single-faced pallets and the separation between faces of double-faced pallets should be approximately 100 mm to permit quick insertion of the handling forks.

The pallet most generally used by the US and UK food industries is the 1,000 × 1,200 mm, four-way entry, double-deck pallet. In continental Europe, the so-called Europallet (800 × 1,200 mm) is widely used. However, many other types and sizes are encountered. Interchange between the different systems is complicated by the fact that pallet racking, pallet-handling equipment, and transport vehicles all function most efficiently when designed for specific pallet sizes. Consequently, the six pallet sizes for use in intercontinental trade listed in Table 5.1 have been agreed by the International Organization for Standardization (ISO 2003). As a result, groups of food manufacturers now cooperate in the operation of pallet pools; see, e.g., http://www.epal-pallets.de/uk/home/main.php. These have now been put on a national basis by a number of service organizations that provide a

Table 5.1 ISO standard pallet sizes

Dimensions, mm (width × length)	Dimensions, in. (width × length)	Predominant region of use
1,219 × 1,016	48.00 × 40.00	North America
1,000 × 1,200	39.37 × 47.24	Europe, Asia
1,165 × 1,165	45.87 × 45.87	Australia
1,067 × 1,067	42.00 × 42.00	North America, Europe, Asia
1,100 × 1,100	43.30 × 43.30	Asia
800 × 1,200	31.50 × 47.20	Europe

Source: ISO (2003). See also Wikipedia (2011)

complete pallet management package. This alleviates one of the major problems of palletization, namely, to provide sufficient pallets of the right type at the right time, on-site, without carrying an excessively large (and costly) stock.

5.1.3.2 Palletization

In palletizing, it is highly desirable to standardize methods of assembling unit loads on pallets and working out an arrangement to utilize the entire area of the pallet. If necessary, a blank space may be left at the center, or an overhang may be allowed if the components are not fragile. Careful packing is necessary to ensure stable loads, and alternate rows may be interlocked to increase stability by placing heavy paper or fiberboard between the horizontal rows of packages or by alternating the patterns to avoid columns within the load.

The assembly of unit loads is time absorbing if carried out manually, and this results in high labor costs. These may be reduced by using an automatic pallet loader. The machine is designed to accept cases or crates of almost any size, providing that the sizes are not mixed. It is installed at the end of the packing line and, as the products are received, an operator, who merely arranges the layer to be loaded, feeds them on to an assembly table. When this has been finished, he presses a push button, which then causes the layer to be deposited on to the pallet and the pallet to be lowered to receive the next load. This sequence is repeated until the complete unit load has been assembled on the pallet. The machine then automatically discharges the full pallet and moves an empty pallet into position ready to receive the next load.

The pallet loader is capable of handling cases and crates at a continuous rate of between 40 and 50 a minute and building them into unit loads of up to 1.5 t. Automatically operated de-palletizers for breaking down and redistributing palletized unit loads on to conveyors, are also available.

5.1.3.3 Overwrapping

If assembled in interlocked or tiered patterns, palletized loads of regularly shaped cartons or boxes may be sufficiently stable to be handled without fastening. Generally, however, it is necessary to secure the load by strapping, taping, or overwrapping. The latter also protects the load against damage and contamination and pilferage.

Stretch wrapping is largely used for palletized goods as the size of the load makes shrink wrapping impractical. The technique employs a wide band of stretchable polyethylene, which is wound round the load under tension by hand or machine. The unit is tightly enclosed when the tension is released and the stretched plastic relaxes.

As well as disposable overwraps, returnable pallet covers can also be used to hold together and protect palletized unit loads. They may also incorporate a thermal barrier to maintain the temperature of chilled or frozen foods.

5.1.3.4 Order Picking

In the distribution process, finished goods are transported from the food manufacturer to the retailer. Although many food manufacturers undertake their own distribution, this is increasingly becoming the province of specialized companies.

Food manufacture is often dominated by relatively large-scale operations. In contrast, storage-space limitations may require the retailer to accept frequent deliveries of a wide range of items. Order picking is the act of assembling the items that make up an order, probably from palletized unit loads. These are consolidated into new unit loads for dispatch.

Where the throughput is rapid and the supply well matched to the demand, the quantity of product requiring to be held in the producer's warehouse can be minimal, and manual order picking at ground level from static or mobile shelving or floor-standing pallets will suffice. The required product mix is assembled, commonly, in a wheeled cage, which can be loaded directly on to a vehicle. If, on the other hand, the goods are held in a high racking system, specialized order-picking equipment, which can traverse an aisle and elevate an operative and loading platform to the appropriate location, will be required.

5.2 Conveying Equipment

5.2.1 Air-Cushion Conveyors

When air is passed through a bed of powdered or granular solid material, the pressure drop over the bed increases with air velocity until it becomes equal to the bed weight per unit area. The air velocity at this point is known as the minimum fluidization velocity. Further increases cause the bed to expand, without any increase in pressure drop. Under these conditions, the bed assumes many of the properties of a liquid and the material is said to be fluidized.

The above principles are embodied in the design of air-float conveyors. The solids to be conveyed are fluidized by air and, as a result, run freely down a small (6–8°) incline in a manner similar to that of a liquid. The conveyor consists of a rectangular duct separated transversely by a porous plate. The upper section houses the material to be conveyed, and the lower section forms a plenum chamber containing low-pressure air, which diffuses through the porous plate and fluidizes the bed of material. A single blower is sufficient to operate a complete installation.

5.2.2 Apron Conveyors

These are constructed from interlinked crosspieces such as slats, pans, or plates, which overlap and which are carried by endless chains. Thus, a robust, leak-proof conveying surface is provided, which is capable of carrying heavy loads and handling hot or abrasive materials unsuitable for belt conveying. Like slat conveyors (see Sect. 5.2.10), apron conveyors may be used to carry out some "on-the-move" processing operations such as meat jointing or boning and vegetable trimming. Apron conveyors, fitted with deep pans and/or cleats, can also be used on inclines up to 45°.

5.2.3 Belt Conveyors

These consist essentially of an endless carrying belt, intermediate supports for the belt, pulleys, take-ups, guides, and a means of driving the belt. The belt may take the form of a continuous sheet, an open wire mesh, or linked, flat strips. Continuous belts of metal or plastic provide a solid, sustaining surface for the movement of a wide variety of both bulk and packaged items. The three commonest plastic materials of construction are acetal, polypropylene, and polyethylene. All three have a good impact and wear resistance, with polyethylene having the highest operating temperature range. They are suitable for horizontal, inclined, or declined movement at angles up to about 22° for smooth belts and 45° for cleated or ribbed belts. Belts may be flat, for packages, or troughed, for handling bulk materials. They may be made of plain or plastic-coated canvas, steel mat, or ribbon and are available in smooth, slatted, cleated, ribbed, walled, and specially profiled forms. Belt widths of 150–2,000 mm are obtainable and conveyors ranging from a few meters to several kilometers long are used. Telescopic belt conveyors have been developed to assist loading and unloading.

Troughed belt conveyors, comprising an endless belt supported by concave or troughing idlers, are used to handle bulk materials, but alternative designs claiming to offer operational advantages are available. These include conveyors formed by running a flat belt on a dished-sheet metal bed and those that incorporate a specially molded belt. The latter is a one-piece molded belt of trough-shaped cross section. Running on parallel rollers, the conveyor is said to operate with reduced spillage, less material degradation and hence dust, and reduced maintenance costs. Bulk materials conveyed include vegetables, grain, granular food products, and offal from slaughterhouses.

Under some processing conditions, it is advantageous to convey bulk materials on flat belt conveyors, particularly if material has to be unloaded at any point along the running belt. Apron conveyors are of value here. However, when used for bulk handling, they usually have side aprons for holding larger quantities of materials. In this form they are sometimes called "pan" conveyors and are limited in operation to a single-point discharge. Steel-band conveyors offer advantages in that they meet the stringent hygienic requirements of food processing, operate satisfactorily when handling sticky or greasy substances, and are also suitable for applications involving the processing of bulk materials during movement by the conveyor. In this case increased load-carrying capacity can be obtained by using side skirt panels.

Proper control of belt tensioning is vital, especially with long conveyors, and this may be achieved using sprung, counterweighted, or screwed adjusters. Control of belt tracking, especially with fast running belts, and effective side guards to protect operatives are other essential design features.

The most careful consideration must be given to the hygienic design and operation of belt conveyors that are used in food handling; both the belts and the drive and support components should be thoroughly cleanable.

The following types of belt conveyor are in common use in food factories.

5.2.3.1 Steel-Band Conveyors

These are belt conveyors that use a flexible steel band as the load-bearing surface. The conveying bands are manufactured in either hardened and tempered carbon steel or hard-rolled stainless steel. The latter is intended for those installations where high corrosion resistance and hygiene standards are required. The mechanical construction of the steel-band conveyor is similar to those of any other belt conveyor, except that larger terminal pulleys are necessary to reduce the stresses in the band that would occur if small pulleys were used. Also fewer idlers are needed on account of the higher mechanical strength of the band.

Steel bands can be employed to advantage in warm localities, such as drying chambers and baking ovens. They may also be adapted to include worktables, on which the materials are subject to some kind of treatment during transportation as, for example, the cutting of meat, sorting and cutting of vegetables, and filling of cans and bottles.

Another useful feature of steel-band conveyors is their capability to act as in-conveyance heat exchangers. This confers considerable advantages in that speed of travel may be accurately controlled to conform exactly to process requirements. Typical examples of such processes include cooling, heating, solidification, and crystallization.

5.2.3.2 Wire-Mesh Belts

Many forms of wire-mesh belt are made to suit different applications. When not exposed to moisture, the belts used in conveyors of this type are generally constructed of bright mild steel wire. Low cost and relatively high tensile strength at normal temperatures dictate the choice here. The material does not begin to flex until temperatures above about 350 °C are encountered. Where maximum resistance to corrosion by moisture or free water is required, wire made from a suitable stainless steel should be used.

5.2.3.3 Woven and Spiral Belts

The simplest form is fabricated by joining right- and left-hand woven wire panels by means of a crimped cross rod. Belts woven in one direction have a tendency to run towards one side of the terminal drums, so by alternating right- and left-hand panels, a straight-running belt is obtained. These belts are mainly suitable for handling light articles; a typical application is as an oven belt for baking biscuits. A similar weave having cross rods and fitted with side plates and side chains is frequently used in deep-freeze tunnels at temperatures down to −40 °C.

Belts of the open-mesh spiral type often satisfy handling operations in canneries and bakeries. Such belts comprise alternating right- and left-hand spirals connected by crimped rods, which ensure that the original shape of the belt is retained. The spirals cannot move when the belt is under tension, and their disposition also ensures straight running. Furthermore, as each coil is independent of the next, the belts are very flexible, and there is little distortion in temperatures up to ca. 600 °C.

In order to obtain very close-mesh belts, it is possible to multiply the number of spirals and cross rods per pitch. This type of belt is frequently used in ovens, especially in baking ovens, where the products are not handled in tins but are placed directly on the belt. A further variant has insets in the spirals; it is used to promote the movement of soft materials, which would penetrate and clog a normal close-mesh belt (e.g., as in the automatic production of cakes).

5.2.3.4 Wire-Link Belts

These consist of single-wire links connected by cross rods on which they are assembled. The edges of the belt are finished by a special washer, welded to each cross rod. Both drive and tail drums mounting the belt have grooves into which the cross rods and loops fit precisely. A positive drive is thereby produced, causing the whole belt to act as a chain. The assembly renders belt slip impossible and the conveyor can easily be synchronized with other conveyors or machines.

Applications occur throughout the canning and general food industries, as in drying tunnels, freezing plant, and sterilizing plant. The construction is particularly advantageous where through-circulation of air is required. Due to the strong welded edges, it is possible to run the belt with only slight play on either side, a feature that forces the air to pass through the belt without short-circuiting to the sides.

As the belts consist of single wires and coils, clogging is almost impossible and cleaning can be undertaken easily without removal of the belt from the conveyor.

5.2.3.5 Woven-Spring Steel Belts

These are used mainly as oven belts for biscuits and other bakery products, which are carried directly on the belt. They are also of value in the drying and blanching of vegetables and fruit. As the mesh of the belt can be very fine, it can easily support dough, which is not contained in baking tins or trays. Moreover, it is claimed that in many cases better results are obtained than with steel-band conveyors. Very little stretch is experienced in operation and, due to the special method of weaving, belt tracking is good. However, as the weave does not consist of separate coils or links, as in spiral- and wire-link belts, it is necessary for the longitudinal wires to bend round the terminal drums or pulleys. This, in turn, necessitates a larger pulley diameter, a minimum of 800 times the thickness of the longitudinal wires. Support rollers along the conveyors can, of course, be of smaller diameter. Very low heat absorption is also a characteristic of woven-spring steel belts. These are typically up to 2 m wide, and made of either round or flat spring steel, welded at the edges, and supplied in almost any length in meshes from 1.5 mm, wire thickness of 0.7 mm upwards.

5.2.3.6 Flat-Strip Belts

These are of bright mild, galvanized or stainless steel strip, assembled on cross rods with either hooked or welded ends. They have good articulation, a large open area, and are easily cleaned. Positive drive without slip is obtained by means of toothed sprockets, the number of which that are fitted to the drive shaft being dependent on the length of the belt and the load on the conveyor. Used generally in bakeries and canneries, these conveyors can be employed in sterilizing and pasteurizing plant, and in freezing tunnels.

5.2.4 Chain Conveyors

Available in many forms, these conveyors are designed for the movement of objects over fixed paths or routes. The simplest type consists of chain with links adapted to drag the material along a trough. The chains may be of metal or plastic (the same as those used for belt conveyors). Slat conveyors and apron conveyors can also be regarded as chain conveyors since their load-bearing surfaces are attached to driven chains.

One or two chains with flat links are also often used for the movement of objects where a circuitous path and sharp corners must be followed—as in bottling operations. Side rails guide the objects being handled. Retractable chain conveyors of this type, set parallel to the axes of the rollers of a roller conveyor and located in the spaces between the roller, can be used to discharge items from a roller conveyor or transfer items from one roller conveyor to another running parallel to it.

Double chains set level with the floor and carrying lugs which protrude above floor level may be used to move heavy items, e.g., drums, short distances. Towline conveyors use a driven chain as the source of motive power for trucks running at floor level, and overhead-chain conveyors move goods on platform hooks attached to high-level chains. Conveyors of this latter type are encountered frequently in the meat and poultry processing industry.

5.2.5 *Flight Conveyors*

Flight conveyors are used for the bulk conveying of materials such as root vegetables. They may be moved along a trough by means of flights attached at regular intervals to an endless chain. Objects can be moved horizontally, down inclines, or up inclines not exceeding 45°.

There are three main types of flight conveyor. These are (a) scraper-flight, (b) suspended-flight, and (c) roller-flight conveyors. The scraper-flight conveyor features a single chain, rope or cable, which pulls the flights along the trough. This is often enclosed when used only for bulk materials. The suspended-flight conveyor also contains a single chain, but the flights are fitted with wearing shoes, which are dragged along the edges of the trough, thereby keeping the flights clear of the bottom. In the case of roller-flight conveyors, the flights are kept clear of the bottom of the trough by rollers running on its edge. For heavy-duty service, a double chain is used, with the chain and flights supported on rollers.

Where products of small particle size are to be handled continuously in bulk, resort may be made to enclosed conveyors of the Redler "En-Masse" type (Redler Conveyors Ltd., Gloucester, UK; http://www.redler.com/en/products/conveyors-eleveyors/). Totally enclosed and dust-tight, these conveyors are extensively used for the bulk handling of materials such as sugar, cocoa, tea, coffee, cornflakes, flour, malt, milk powders, nuts, grain, salt, and starch. Unlike ordinary flight conveyors, which push the materials along the conveyor trunking, the system features submerged skeletonized flights, which, as a result of its cohesiveness, induce product to flow along the conveyor almost as a solid core. A particular advantage is that these conveyors are exceptionally compact.

5.2.6 *Overhead-Chain Conveyors*

The overhead-chain conveyor is, perhaps, one of the most useful of handling devices. Comprising a monorail or similar runway, load-bearing trolleys, and an endless chain drive, it is a simple, flexible, and economical method of transporting materials from point to point on a fixed line of travel. It saves valuable floor area, thereby avoiding congestion and permitting straight-line production without costly building reconstruction.

Loads are carried by means of hooks, racks, special carriers, or suspended trays. The track may be arranged to drop at predetermined points to permit loads to be removed from or placed upon their carriers. Semiautomatic operation can be achieved by using automatic discharge or dumping stations for trays, upending and loading devices, and automatic transfers. The load-carrying hooks or trays can easily be adapted to the automatic devices and may be made to any shape or form required by the load.

Telescopic units have been developed, which can extend from a loading bay into a lorry to facilitate loading and unloading when unpalletized goods are being handled.

5.2.7 *Roller Conveyors*

These comprise spaced rollers mounted horizontally in a frame supported on stands or trestles so as to form a table on which packages may be conveyed either horizontally or down a slight incline. Gravity-actuated roller conveyors are cheap and effective and require a gradient of only about 3 % to effect transfer. They are available as kits of standard parts, which can easily be assembled, extended, repositioned, or dismantled. They are also available as fully mobile, wheeled units which can be extended, adjusted for height, and bent around curves up to 180°.

Heavy-duty roller conveyors may be powered by endless driven chains, which engage with sprockets built into the ends of the rollers. Light-duty systems are driven by belts, which are mounted beneath and in friction contact with the rollers. Driven rollers may, of course, be used for true horizontal movement, thus avoiding the problem of working height loss, which is unavoidable with the gravity-actuated systems already described.

Change of direction on conveyor lines is usually effected by the use of tapered rollers since straight rollers tend to move the load straight ahead rather than around the curve. Transfer of loads from one line to another can be arranged by using switches of various types; these may be actuated manually or automatically. Other devices used to transfer loads include rotary transfer tables and ball tables.

Transfer cars, located on track running along one end of the lines, can be used to move loads between parallel conveyors. Movement of a load between conveyors running at right angles to each other can be effected by rotary-transfer or ball tables. The latter are more readily adapted to production conveyor lines and can be used as work or inspection tables and, when fitted with scales, as weighing platforms.

Determination of the proper type of roller conveyor to be used requires the compilation of certain basic information, such as:

1. Maximum and minimum dimensions of items to be conveyed
2. Maximum and minimum weights of items to be conveyed
3. Full particulars of the actual riding surface of the items
4. The kind of material out of which the item in direct contact with the conveyor is made

For units that have a hard, smooth-riding surface, such as wooden cases, the length of the roller is normally equal to the width of the load. In some cases, it may even be less provided that overhang is not a problem. When cartons are to be conveyed, the usual practice is to employ a roller 50 mm longer than the maximum width of the carton.

To convey an object having a smooth, hard surface, at least three rollers are required under the object at all times. The greater the number of rollers, the smoother is the operation. If the load is such that the load per roller is greater than its rated capacity, then it will be necessary to employ a closer roller spacing, to use a heavier type of roller, or to interpose a load board. Care should always be taken to ensure that the total weight of the load never exceeds the total rated capacity of the rollers supporting the load.

The main advantages of these conveyors are their flexibility, their large capacity in relation to the occupied space, and their relatively low power consumption. Possible disadvantages include the hindrance that they offer to the movement of staff and mobile equipment and the fact that they are not self-loading.

5.2.8 Screw Conveyors

Screw or worm conveyors provide dust-tight fully protected bulk conveying for many classes of food products. They comprise a continuous or split-flight helix mounted on a rotating spindle, the whole of which revolves in a suitable trough. The resulting screwing action propels the material being conveyed from one end of the trough to the other. Various forms of screw are employed: crescent-bladed, paddle worm, continuous spiral, and open spiral. The first two of these, the crescent-bladed and the paddle worm, are useful because it is possible to reverse the movement of the material in the conveyors by reversing the pitch of the blades. Delivery at any point in the conveyor can be arranged by fitting suitable open chutes along its length.

The flared trough conveyor is specially designed for use in meat and bone plants and is capable of dealing with materials ranging from quartered carcasses, which ride above the screw, to meals which are conveyed lower in the trough. The flared profile prevents pieces of bone and meat wedging and allows a large volume of material to be piled on top of the screw. There are no intermediate bearings to obstruct conveying. The screw runs on brass strips in the trough.

The screw elevator is constructed on similar principles to the screw conveyor and is used for light duties. Considerable friction is involved and power consumption becomes excessive at lifts above about 5 m.

The combination of screw conveyor and elevator provides for both horizontal and vertical movement of materials. Screw conveyors are capable of producing uniform discharge and may thus be used as feeding or metering devices. The flights and casing may be hollow and equipped to carry hot water, steam, or chilled water so that in-conveyance processing can be carried out.

5.2.9 Skate Wheel Conveyors

Skate wheel conveyors, sometimes called wheel- or gravity-wheel conveyors, are widely used in low-cost, fixed, and temporary-handling applications. They comprise free-running wheels mounted in groups of three or more on horizontal axles carried in a light frame so as to form a carrying table. Packages or goods with firm flat bases large enough to span at least 6 wheels (2 across and 3 along the conveyor) are moved manually in a horizontal plane or by gravity along a slight decline (approx. 3 %).

Although similar in application to roller conveyors, wheel conveyors differ in the following ways:

1. Rollers are more robust than wheels and can carry heavier loads.
2. Wheels offer less friction with packages than rollers and hence are better on curved conveyors.
3. Wheels have much lower inertia than rollers and it is therefore easier to initiate and arrest movement on wheel conveyors.

5.2.10 Slat Conveyors

Slat conveyors feature a carrying surface made of wood or metal slats, which do not overlap or interlock, attached at their ends to two roller chains usually running in steel guides. The load can be placed directly on the slats or in containers. The conveyor itself may be placed at work height or floor level. The apron conveyor is a modification of the slat conveyor, in that the slats overlap each other to form a continuous, leak-proof moving surface.

The maximum angle of inclination is approximately 10° with a slat conveyor, but this may be increased to 45° by using cleats or flights, depending upon the type of materials being handled.

5.2.11 Spiral Conveyors

Vertical movement of materials may be effected by spiral conveyors. These are of two types: (a) spiral roller conveyors and (b) spiral chutes. Both serve the same purpose, namely, that of lowering articles from one floor to another, or from a higher to a lower level. They can be made to serve any number of floors. Loading and unloading stations can be arranged on any or all floors according to requirements.

Spiral roller conveyors consist of a number of curved sections of roller conveyor set in the form of a spiral, with a slope varying from 5 to 10°. They offer several advantages over other methods of lowering articles in (a) requiring no power, (b) permitting a slow and easy descent, (c) allowing for considerable storage, and (d) conveying open containers or trays without spilling the contents and fragile articles without damage. Of the standard types, the tapered roller gives the best results as it reduces friction between the load and the outer guard rail.

A spiral chute consists of a smooth-surfaced inclined trough fashioned in the form of a spiral. These conveyors are limited in their application because of the steep pitch required to overcome friction. The feed and discharge chutes join the spiral chute tangentially. A hinged deflector is mounted on the discharge chute to divert articles from the spiral chute.

Articles that do not require particularly gentle handling, such as boxes, crates, bundles, and cases, can be conveyed efficiently by spiral chutes. Roller conveyors are better when careful handling is necessary.

5.2.12 Pusher-Bar Conveyors

The pusher-bar conveyor is the best type to use for elevating or lowering loads at angles between 30 and 60° or greater. It comprises two endless chains connected at intervals by bars or rotatable pushers, which propel the material along the bed or trough of a conveyor. They are simple to operate, have a low initial cost, and are easily adapted to automatic loading. They are particularly useful as a means of elevating packages from one section of a roller conveyor to the next, i.e., when the conveyor is of such a length that continuity of motion under gravity is lost.

5.2.13 Towline Conveyors

A towline conveyor consists of a series of floor trucks connected to an overhead chain, driven by a synchronous motor and pulling the trucks over a defined circuitous route. Alternatively, it may be driven by a chain operating in a channel below floor level. Such conveyors find use in large warehouses or storerooms as a means for distributing incoming goods or gathering items for outgoing orders. They may also be used as continuous moving storage for supplying manufacturing areas. A more elegant alternative is the use of automated guided vehicles (AGVs) (see Sect. 5.9.2.1).

5.2.14 Vibrating Conveyors

The bulk conveying of many materials may be accomplished in metal troughs, which advance the materials by means of reciprocating or vibrating action. Movement is secured either by exploiting the natural frequency of a spring-supported mass or by electrical means.

Natural frequency mechanical vibrating conveyors consist basically of a trough mounted on a rigid base frame by means of coil or leaf springs, or a combination of both, and connected through a suitable linkage to a motor-driven eccentric shaft. The springs store energy on the downstroke, which is released to the conveyor trough in “natural frequency” impulses requiring a minimum of external force on the upstroke. Each spring acts essentially as an individual drive unit.

Electric vibrating conveyors comprise one or more electrically driven eccentric motors mounted on the conveying trough. These give rise to oscillatory forward and backward motion of the conveying surface. This action takes place at high frequency and at a small, variable amplitude or stroke. The conveying rate can be varied precisely by controlling the amplitude and/or frequency; hence, vibratory units are often used as feeding or metering devices. Furthermore, since movement is induced by high-frequency motions of small amplitude, vibratory conveyors are characterized by gentle transfer and may thus be used to move fragile and delicate materials such as potato chips, biscuits, and wafers.

Vibratory conveyors are available for horizontal, incline-up, incline-down, or vertically up and down motion. In the latter case, a spiral conveyor is used. Conveying is substantially dust-free and troughs may be totally enclosed for added material protection. In addition, process operations such as drying, screening, or sorting may be performed while the materials are being conveyed.

5.3 Chutes

A chute is a smooth-surfaced inclined trough on which bulk materials or individual items are lowered under gravity. Chutes may be straight, curved, or spiraled. Objects will slide down a chute only when the frictional force between the package and chute surfaces is overcome. A similar consideration applies to the movement of bulk materials on chutes, but in this case we are concerned with friction between the contact surface of the bulk material and the chute surface. Unfortunately, the so-called laws of friction are not fundamental; they are working approximations and their effective application requires much experience. While the concept of conveying by gravity on a chute is most attractive and apparently simple, many design and operating factors must be considered. Among the more important ones are the nature of the contacting surfaces, the chute length and inclination, and finally, with bulk materials, the nature of the flow.

5.4 Cranes and Hoists

5.4.1 Cranes

A crane is a lifting or lowering device that is motivated by a source of power remote from the load hook (as distinct from a hoist) and which is carried at the end of a boom or jib. The boom pivots on a mast, which is supported by fixed legs or which is guyed by ropes or cables. The unique capability of cranes to lift objects below their support level, combined with their lift and swing characteristics, makes them indispensable for loading and unloading ships, barges, railway trucks, etc.

An overhead traveling bridge crane (or more correctly, hoist) can service the width and length of the area encompassed by its runways. It carries its load suspended from a trolley carried on two transverse beams. The load may be lifted and lowered, caused to transverse the support beam and/or move along the transverse beams giving accurately controlled three-dimensional movement.

A pillar crane is a fixed-elevation jib crane. These find many applications ranging from retort charging to the handling and positioning of heavy packages and equipment.

5.4.2 Hoists

A hoist differs from a crane in that the load is attached directly to the motivator, which is suspended from a fixed point or a horizontal beam. Fixed-point mounting is provided where only vertical lifting is required for, say, loading and unloading wheeled transport. Beam mounting is used where the hoist is required to service a wider area. The beam may be fixed, pivoted at one end so it can be moved through an angle, or mounted on rails so that it can track in a direction perpendicular to its length.

Hoists may be manually, electrically, or pneumatically powered, the loads being carried, raised, or lowered on chains or wire ropes. Some form of gearing is normally employed to increase the mechanical advantage.

5.4.2.1 Pneumatic Hoists

Pneumatic hoists are sparkproof, safe in dusty conditions, cheap to maintain, and resistant to corrosive, hot, or humid conditions. They are of two types, cylinder and air-motor. Both types operate by compressed air, are economical to install and use, and provide smooth, accurate control of the load. Cylinder hoists may be either single- or double-acting. The latter provides more accurate control. Air-motor hoists require a greater initial investment than cylinder hoists but are as economical to operate and maintain. The motor is totally enclosed and an automatic brake holds the load at any position, even when the air supply is shut off.

5.4.2.2 Electric Hoists

These range in capacity from 1/8 to 30 t and have a far wider application than chain or air hoists when high speeds are required for economic operation. They are designed to meet varying needs in operation and are furnished with one or two motors, single- or multiple-speed control, and push-button, pendant-rope, or remote-operating facilities. Other desirable features include travel limit switches, radio-controlled units, and creep-speed controls for accurate positioning of loads. Two brakes, one mechanical and the other electrical, should be provided on electric hoists.

5.5 Elevators

It is possible to divide elevators into two major classes: (a) package elevators for individual objects and goods in containers and (b) bulk elevators for loose material.

5.5.1 Package Elevators

Package elevators are of three main types, namely, (a) rigid-arm elevators, for short lifts; (b) swing-tray elevators, for either long or short lifts; and (c) finger-tray elevators, mainly for relatively long and heavy lifts.

5.5.1.1 Rigid-Arm Elevators

This is the simplest type of elevator for raising packaged materials vertically or at large angles. It is a simple, inexpensive, compact, and efficient labor-saving device. It consists basically of two endless chains or belts running over top and bottom sprocketed wheels, to which rigid arms that carry the load are fastened at specific intervals. The rigid arm picks up the load at the loading station and discharges it over the top of the terminal pulley. The running gear is perfectly balanced and the speed slow; the power absorbed in lifting a series of loads (barrels, bags, boxes, etc.) is often so small as to be almost negligible.

5.5.1.2 Swing-Tray Elevators

The rigid-arm elevator has its limitations, as it is unsuitable for serving several floors and for lifting breakable goods. Of more widespread use is the swing-tray elevator, which is well suited for lifting and lowering goods in bottles, cans, baskets, crates, or other containers through any required number of floors.

The machine consists of two endless chains or belts running over chain wheels at the top and bottom. At intervals, swinging trays are suspended between the chains. These act as pivoted carriers that always maintain a horizontal position, as their center of gravity is well below the point of suspension. It is usual to locate the drive motor at the top of the elevator and the tensioning mechanism at the bottom.

It should be observed that no harm is done if loads are left on the swing trays, as they merely go round and round the circuit. Carefully designed and foolproof guarding of the charge and discharge points is obligatory. Although the load-carrying capacity of the carriers may be quite high, the effective capacity of these elevators is controlled by the “lift-on–lift-off” capacity and by the intermittent nature of the charge and discharge arrangements.

The swing-tray elevator caters for many materials-handling applications. However, there are instances where even the swing experienced with these trays may be sufficient to give rise to serious production problems. These can be eliminated with the aid of a stabilized tray.

5.5.1.3 Finger-Tray Elevators

These are similar in construction to swing-tray elevators, but they incorporate automatic charge and discharge gear, which allows safe, substantially continuous operation in multistory buildings. Effectively, the swinging trays consist of “fingers,” which pass through matching gaps in hinged roller platforms located at the conveyorized charge and discharge points. Packages charged to a loading platform are picked up by the ascending fingers on the up leg and are discharged by the descending fingers on to discharge platforms on the down leg. The location of the charge and discharge points can be altered by raising or lowering these platforms.

As with other mechanical elevators, stringent safety precautions are necessary with these devices.

5.5.2 Bulk Elevators

Bulk elevators, for loose materials, include bucket elevators (described below) and elevators which function on the screw, flight, and pneumatic conveying principles. These are discussed elsewhere in this chapter.

Bucket elevators are high-capacity machines used primarily to elevate relatively free-flowing materials that discharge cleanly. They comprise metal or plastic buckets, which are carried on a pair of endless chains, running in a casing. The material to be conveyed is fed into the bottom (or boot) of the casing where it is dredged up by the buckets and ultimately discharged through a chute at the top of the casing.

Four main types of bucket elevator are recognized. These are characterized by the type of discharge method employed, i.e., gravity, positive, centrifugal, and continuous discharge. Gravity-discharge bucket elevators use high-capacity buckets carried at low speeds (0.25 m/s), which are tipped mechanically. This system is often used in conveyor–elevator applications. Positive-discharge bucket elevators use closely spaced small-volume buckets, which are tipped by means of change-of-direction sprockets located on the downside of the conveyor chain. Centrifugal-discharge bucket elevators are high-capacity machines, which discharge the conveyed material centrifugally into the outlet chute. In this system, the drive speed is critical (typically 1.5 m/s) if the material is to be thrown cleanly into the outlet chute. At these high speeds, wear and tear is considerable and precautions need to be taken with foods that exhibit dust explosion risks. Continuous-discharge bucket elevators run at low speed (0.5 m/s) with closely spaced buckets. A clean discharge results from using the backs of preceding buckets as chutes.

5.6 Magnetic Handling Systems

Magnets are used to hold and move either ferromagnetic packages (e.g., tinplate cans) or their contents. Either permanent or electromagnets can be used.

Other types of magnetic equipment include magnetic rails, which are used to convey and orientate cans (e.g., for washing or inspection). Magnetic elevation and conveying may be effected by running a flexible belt above and adjacent to a static magnetic field (e.g., rollers), which holds magnetizable units on the belt and allows the articles to be moved through vertical and horizontal planes.

5.7 Manual Handling

While there is still a role for manual handling in the workplace, there are limitations, e.g., on weights that can be lifted on a single or repetitive basis. Mechanical devices such as hand trucks have therefore been developed to assist manual operations. Self-leveling tables are also available to enable manual palletizing to take place at a height convenient for the operative. Mechanical lifting aids such as pneumatic manipulators can assist in lifting loads up to 250 kg.

5.8 Pneumatic Conveying Systems

Pneumatic conveying is widely used for bulk conveying large volumes of dry, free-flowing materials such as cereals, sugar, salt, and flour. Properly engineered, these systems are dustless and hygienic since conveying takes place in a totally enclosed environment. They are relatively cheap to install and operate and they are substantially self-cleaning. The same system can therefore be used to convey a variety of materials with minimum cross contamination.

Centrifugal fans and Rootes-type rotary-piston blowers are commonly used to move the air in pneumatic conveying systems. The material to be conveyed is fed at a controlled rate into the air stream by specially designed valves. Pneumatic conveyors may be of the positive pressure (or push) type in which material is blown from one inlet and may be delivered to any of several outlets. Alternatively, a negative pressure (or pull) system may be used in which material is sucked into a single receiver from any of several inlet points. Combination push–pull systems, delivering from multiple inlets to multiple outlets, are also used.

The conveying air must be filtered before use and care should be taken to control its humidity in order to avoid either excessive dehydration or wetting of the product. Static charging can cause sparking, which may act as an ignition source for combustible materials. It may also result in electric shocks to operatives. Proper grounding of trunking and pipelines is therefore essential.

Materials from storage bins are discharged into the conveying system through rotary feeders. For coarse, free-flowing materials, a gravity-type feeder is occasionally employed, but for fine materials, such as flour and sugar, which are sometimes sticky, a pneumatic-discharge airlock is much more satisfactory. Rotary feeders are also used. Cyclone separators are normally employed to separate the conveyed solids from the conveying air. After separation the material is discharged from the base of the cyclone through a rotary valve. If necessary, the air leaving the cyclone can be passed through a secondary separator, such as a bag filter, to remove all traces of dust before it is discharged to the atmosphere.

5.9 Trucks

Trucks offer a flexible method of handling materials for intermittent moves. They may be divided into three classes: (a) hand trucks, which are operated and propelled manually, (b) powered trucks, which are propelled by an onboard motor; and (c) tractor-trailers, where one or more unpowered units are towed by a separate prime mover.

Trucks may also be categorized according to their lifting mode. Platform trucks are wheeled platforms on to which material must be loaded or unloaded, either by hand or by some separate piece of equipment. Low-lift trucks are able to engage with and lift pallets off the ground just sufficiently to allow them to be moved freely. High-lift trucks are able to elevate unit loads, stack them, or locate them in vacant spaces in racking systems.

5.9.1 Hand Trucks

In spite of the emphasis on mechanization, manually propelled trucks are widely used in confined areas or when intermittent demand is encountered. Hand trucks are available in a wide variety of designs, including no-lift, low-lift, and high-lift types, and are relatively inexpensive. On good working surfaces, a single operator can conveniently handle loads of up to 1 t. Equipping manually propelled trucks with hydraulic or electrohydraulic lifting gear substantially extends their range of application.

Examples of hand trucks generally encountered in the food industry include sack trucks and drum dollies (no-lift), hand pallet and stillage trucks (low-lift), and manual stacking trucks (high-lift), which are available with forks, platforms, or jib-crane attachments.

5.9.2 Powered Trucks

There are three classes of powered industrial truck-handling systems, namely, (a) no-lift trucks such as the tractor-trailer platform truck, (b) low-lift trucks such as pallet or stillage trucks, and (c) high-lift trucks such as forklift and stacking trucks.

Numerous special types of powered truck have evolved for handling a wide range of commodities. Various forms of power are employed, but for food processing establishments, where fire and fume hazards are of major importance, the obvious choice is a battery-powered electric vehicle. These are highly efficient and flexible, and in most applications offer lowest operating costs. The alternative to battery power is the internal combustion engine. Diesel and petrol units should be avoided in food factories as they produce unacceptable exhaust fumes. Liquefied petroleum gas (LPG) is a cleaner alternative. Although LPG-powered trucks can be fitted with exhaust purification systems, they can only be used in well-ventilated areas.

In order to select the transportation system best suited to the job, it is necessary to know (1) the distance to be traveled, (2) the weight handled per trip, (3) the number of trips per work shift, and (4) the number and height of any tiering operations. The choice of truck type will be influenced mainly by the distance traveled and the types of journey envisaged. The weight handled per trip, or the size of a unit load, will automatically determine the required size or load-carrying capacity. The number of trucks needed to handle the work involves a practical engineering calculation.

The ideal handling system is one that involves no wasted movements and requires no manual handling. The fork truck-pallet and the lift truck-stillage systems closely approach this ideal. These are therefore the natural first choices. The former is the most widely used of all and, in small plants, is likely to be first choice. It is generally best for vehicle loading and tiering because pallets are preferable to stillages in such operations. Where loads are heavy and tiering or lifting to vehicle deck height are unimportant, the low-lift truck-stillage system has advantages over the fork truck-pallet system in that loads are not carried in an outboard position and no counterweight is needed. As a result, less dead weight must be moved for a given load.

Where warranted by the volume of work, both systems can be used, the fork truck-pallet system for tiering and vehicle loading and the low-lift truck-stillage system for other hauls. If long distances are to be traveled or load weights are excessive, tractor-trailers have advantages. Loads may be narrower and more of them hauled in one trip. Haulage costs may also be lower.

The tractor-trailer system must be provided with an external means of loading and unloading. If these operations have to be performed by hand, the cost might easily outweigh any savings in haulage costs. However, the fork truck-pallet system can be integrated with it by the simple expedient of using the fork truck for setting pallet or stillage loads on the trailers. A fork truck would also be necessary for unloading at the destination if manual rehandling of individual pieces is to be avoided.

The following conditions within the factory should normally be considered when selecting a suitable powered-truck-handling system: (a) type and condition of the floor, (b) minimum height and width of doors on transportation routes, and (c) minimum width of intersecting right-angle aisles. Floors should be hard, smooth, and level. All doors and aisles should be large enough for easy passage of the largest truck and load. Good practice involves making aisles in working areas wide enough to enable two trucks to pass each other with ease. In storage areas, where space is at premium, one-way traffic is essential for all aisles used only as roadways. Intersecting aisles should be of equal width, the minimum permissible. This information may be secured from the vehicle manufacturer's literature. However, allowances may have to be made for the anticipated width or length of the loads carried by low-lift or fork trucks.

It is not possible to lay down any hard and fast rules about what systems of control should be used to operate a trucking system; this will be governed principally by the layout of the plant and the nature of its products. Where power-operated trucks are used to any marked extent, the following options are available:

1. Assign a given number of trucks to individual departments, each of which is responsible for the onwards movement of materials.
2. Dispatch trucks from a central control point when called for by departmental managers.
3. Employ centralized control, with trucks making scheduled trips at regular intervals on specified routes.

System (3) often offers the most advantages. The control department can plan effective schedules from day to day to meet the demands of production. This results in a high utilization of both equipment and labor.

5.9.2.1 Automated Guided Vehicles

AGVs are referred to variously as AGVs, robot trucks, or robot trains. As its name suggests, an AGV is an automatically controlled, driverless vehicle, which is capable of carrying loads or towing trailers. Two guidance systems are commonly employed. The first utilizes a guide wire embedded in the floor; the AGV's motor is inductively coupled to it and receives guidance from it. Alternatively, photoelectric sensors on the vehicle track colored lines painted on the floor. Both systems have advantages and limitations. Embedding wires is costly and may impair the hygienic status of the floor. However, once they are installed, such systems are usually trouble-free. Painting guide lines on floors is cheap and easy, but they are subject to interference and deterioration. Both systems restrict the movement of the vehicle to a predetermined route, and smooth, well-maintained floors are vital to reliable operation.

Many of these disadvantages have been surmounted by the development of a guidance system that permits free-path movement of AGVs. The GEC/Caterpillar system uses a computer to signal the required vehicle route in the form of a series of X–Y coordinates. The computer also selects the best route for the vehicle and provides speed, stop, and traffic-light control. Passage of the AGV is electronically mapped, but in some cases (e.g., when using the vehicle to stack or collect pallet loads), a more precise knowledge of the vehicle's position is necessary. This has been accomplished by fitting an odometer and a low-intensity rotating laser to the truck; the latter is used to scan bar codes positioned along possible routes.

AGVs are available with a wide range of attachments, such as forks; roller-, slat-, and chain-conveyor load transfer devices; ultrasonic proximity alarms; and infrared and radio communicators. They can be programmed to carry out specific functions, for example, to drop off or pick up loads at specified locations on predetermined routes. Capacities range from 0.5 to 6 t but over half the current installations are designed to handle 1 t or less.

5.9.2.2 Forklift Trucks

These vehicles feature load-carrying forks and are primarily used for lifting purposes; their continuous use for journeys exceeding 100 m is uneconomical. They are widely used in food factories to elevate loads by, typically, up to 3 m. However, high-lift trucks (see Sect. 5.9.2.3) with lifts of 8–10 m are available, and specialized units for servicing high racking systems can cope with even greater lifts.

The forks are normally supported on a high mast, which, in most cases, is mounted in front of the driver. They are raised and lowered by means of a hydraulically powered chain belt. A tilting mechanism on the load rack enables the forks to be angled 10–15° backward and 3–5° forward to cradle the load and facilitate unloading, respectively. Masts may be fixed or forward moving, as in reach trucks, or may swivel to turn the forks. They may be of the counterbalanced or straddle types—the load being either counterbalanced about or carried between the front wheels. The higher the mast, the greater the tendency for it to sway and the greater the difficulty in accurately positioning loads.

In an alternative design (the JCB Teletruk; http://www.jcb.com/products/MachineOverview.aspx?RID=13), the traditional mast has been replaced with a rear-mounted telescopic boom, which, among other advantages, improves driver visibility. Extensive use is made of onboard computer technology to optimize operation. The vehicle is of comparable size to conventional forklift trucks and can lift loads up to 3 t to a height of around 5 m. It can also move the same load out a distance of up to 3.3 m in front of the vehicle.

Many types of fork trucks are available for specialized purposes. In the main, however, standard units of the desired capacity fitted with alternative handling attachments may often satisfy these requirements. Thus, while some objects may be picked up by the standard pallet forks, such loads may be better handled, and in some cases can only be handled, by chisel point forks. Extensions may be fitted to conventional forks for handling long or oversize crates.

Other attachments extending the use of the truck include:

- Crane attachments for lifting unit loads
- Rotating heads, which turn the load through 180° and thus allow the contents of drums, bins, etc. to be poured or emptied
- Backrests for supporting high loads
- Squeeze clamps for the easy handling of boxes, bales, drums, and loads not requiring pallets
- Push frames to assist in the removal of the pallet load, clamps designed to draw the load on to the forks, scoops for the handling of bulk materials, etc.

5.9.2.3 High-Lift Trucks

The very extensive use of palletized unit loads, in particular of raw materials and finished goods, combined with the requirement to make the maximum use of storage space, leads to pallets being stacked. They may be tiered directly on top of one another or slotted into a skeletal steel racking system. Where the racking system is very high, e.g., 8 m, and the aisles are narrow, the use of dedicated high-lift trucks to lift and stow the loads is required. This equipment is more specialized than conventional forklift trucks and often highly automated. Units may be either dedicated to movements within aisles, with subsequent movements being carried out by low-lift or platform trucks, or they may be confined to a single aisle. They do not have the freedom of movement normally associated with trucks; they are in effect dedicated fixed-path AGVs.

5.9.2.4 Low-Lift Trucks

These are self-loading trucks, which carry their loads on a pallet or skid (stillage). They are fitted with forks that pick up the load and raise it just sufficiently (5–10 cm) to clear the ground. Manual, mechanical, or hydraulic lifts are available. Low-lift trucks are very maneuverable, have low dead weight, and are a cheap and effective method of moving unit loads in restricted situations at speeds of up to 15 km/h.

An alternative design, the platform truck, features a load-bearing platform rather than forks. Both types are dictated to the movement of goods over relatively short distances, where the use of a tractor-trailer is not warranted. Their most outstanding characteristic is the embodiment of self-loading features, which enable one truck to service a number of production points without the need for external assistance.

5.9.2.5 Tractor-Trailer Systems

This is considered the most efficient method of hauling materials because the motive unit is separate from the carriers. This enables the load to be pulled rather than carried and permits greater utilization of the tractor. The system is flexible in that the tractor-trailer train is not confined to any fixed path but may be routed and systematized to tie into production schedules. Moreover, as the loads are always on wheels, they may be moved short distances by hand.

The principal features of the tractor-trailer system are as follows:

- Various types of trailer are available for handling different loads, e.g., platform trailers for yard service, dump bodies for bulk materials, box bodies for small-unit packages, and dollies for barrels and objects too heavy for platform trailers.
- They can be used for transporting goods over long distances (over 100 m).
- They have a higher handling capacity than any other system.
- The tractor is not tied up while trailers are being loaded or unloaded. Provided loading and unloading facilities are available at the terminals, three sets of trailers can be serviced simultaneously—the first being loading, the second being unloading, and the third being in transit.
- They are useful for collecting and dispatching loads to a number of locations, often on a regular route as a production express service. Driverless trains (AGVs), electronically controlled and running on programmed routes, are becoming increasingly popular.

5.10 Handling of Liquids

5.10.1 Pumps

The transfer of liquids is often effected by gravity, but for many purposes the use of pumps is more effective. These may be divided into four main categories: centrifugal pumps, reciprocating positive-displacement pumps, rotary positive-displacement pumps, and air-displacement systems.

The selection of an appropriate pump is governed by many different factors. These include, for example, the physical characteristics of the feed (e.g., clean liquid, liquid containing suspended solids, paste), the viscosity of the feed, the required capacity and head (pressure difference developed across the pump), the service to be performed (continuous, intermittent, or standby), and hygiene requirements.

Centrifugal pumps are used for pumping low-viscosity food products and cleaning fluids. Positive-displacement pumps are used for pumping thicker more viscous materials and those containing small particulates. Piston pumps can handle thick viscous fluids and dry lumpy products such as meats. Diaphragm pumps are used for pumping liquids and for dosing. Irrespective of the type of pump used, it is essential that its material of construction does not react with the substances handled, including any sanitizing fluids, and that the interior of the pump is at all times readily accessible for cleaning. For further guidance on pump selection, consult Green and Perry (2008a).

5.10.2 Pipelines

Considerable care should be taken in the design of a pipeline layout for conveying liquid foods to ensure that the resistance to flow is kept to a practical minimum. The special requirements of food processing demand that the pipeline should comply with strict hygienic design standards, including the avoidance of obstructions, wells, or “dead ends” where contaminants can accumulate and avoid sanitization. Bends should be smooth and of wide radius. Sharp corners should be avoided and the pipeline should be sloped so as to be self-draining. Although dismantling and cleaning of pipelines is still widely practiced, cleaning-in-place (CIP) is increasingly employed. In this method, detergents and sterilants are forced through the intact pipework. For further details, see Chap. 4.

As with all plants, which may come into contact with food products, the materials used to construct pipelines must be smooth, nonabsorbent, abrasion- and corrosion-resistant, non-contaminating, and unaffected either by the food or cleaning agent employed. This restricts choice to a few materials such as stainless steel, glass, and some plastics. Other considerations affecting pipeline selection include temperature and pressure of operation, physical properties such as mechanical strength and impact resistance, and thermal properties such as conductivity, which will affect lagging requirements.

5.10.3 Flow Measurement

Various techniques are used to measure the flow of liquids and gases. Some of the more common methods include orifice plates, Venturi meters, rotameters, positive-displacement meters, magnetic flowmeters, ultrasonic flowmeters, and Coriolis mass flowmeters. For further details, see Green and Perry (2008b).

5.11 Accumulation and Intermediate Storage of Materials

5.11.1 Accumulation

If supply were matched to demand at every stage of manufacture, distribution, and sale, there would be no need for intermediate storage. The “Just-in-Time” (JIT) philosophy of manufacture seeks to approximate this situation by appropriate design of the production and supply systems. It utilizes a clear flow of information in the opposite direction to the product flow to enable downstream circumstances to control upstream operations. Where, as frequently happens, there is a temporary mismatch between the rate of supply from one operation and the rate of demand from the next, an accumulation system is needed to maintain a buffer stock. At its simplest, products may be allowed to back up along the conveyor linking the two operations. Alternatively, items on the conveyor may be diverted by sweep bars on to a second belt, moving parallel to the first but in the opposite direction. A second set of sweep bars subsequently re-diverts them back on to the original conveyor, thereby completing a circulatory accumulation system. Alternatively, an accumulating table may be provided.

5.11.2 Intermediate Storage

Intermediate storage is another example of accumulation. Perishable products are often stored prior to order picking and/or dispatch, and it is important to maintain a “first in–first out” system of stock rotation. In intermediate storage, this is achieved automatically through the use of a racking system, which allows product to be delivered at one side of the racking, move through it in sequence automatically, and be retrieved as required from the other side.

The same concept may be applied to the handling of complete palletized unit loads. However, the advent of computer-based retrieval systems offers an alternative. Pallets can be placed in any location in a racking system, their location being automatically recorded. They may subsequently be retrieved in the order of production.

5.11.2.1 Bins and Tote Bags

Bins should stack conveniently when filled to allow unit loads to be built up. They should also nest neatly when empty. Plastic moldings can be shaped so that one bin will stand firmly on another when in one orientation but will nest when the orientation is reversed.

Collapsible cubic bins may also be mounted on pallets. A disposable plastic liner is placed inside the erected bin, which is subsequently filled with a liquid product and sealed. Once emptied the bin can be collapsed for return and storage before reuse.

Tote bags are often used to store in-progress materials as well as bulk ingredients. These bags, often containing loads up to 1 t, can be lifted and moved using forklift trucks, cranes and hoists, or other suitable handling devices.

5.11.2.2 Racking Systems

While pallets can be stacked one on top of another, the number of units so stacked is limited by the compressive strength of the unit loads. If each pallet is supported in one cell of a racking system, this limitation is removed and a better utilization made of the building height. The simplest racking systems consist of three-dimensional support scaffolds, and systems 30 m high are not unknown.

To make fullest use of the building capacity, the highest possible fraction of the floor area must be devoted to pallet storage. However, the aisles must be sufficiently wide for handling equipment such as forklift trucks to maneuver and be positioned at right angles to the rack face when inserting or removing loads. To limit the aisle width required, reach trucks, which have forks that can move forward to insert pallets two deep, may be used, thereby halving the number of aisles required. Alternatively, mobile racks with limited movement perpendicular to their face may be employed. Space need then only be provided for one aisle, which can be opened up as required between any two racks.

Another strategy is to use automated racking and handling systems where the pallets are moved in and out of the racking by dedicated, unmanned equipment, mounted on guide rails operating in an aisle little wider than the unit load itself.

5.12 Weighing

Manual weighing using counterbalancing weights has now been replaced, in most cases, by systems utilizing transducers linked to microprocessors. Several different types of transducer are available, but the load cell incorporating strain gauges is the most widely used.

5.12.1 Load Cells

A load cell comprises a stainless steel or aluminum alloy block to which strain gauges are rigidly bonded. The strain gauges are usually arranged to form a Wheatstone bridge. Flexing of the cell generates an output voltage, which can be related to the applied load. The cell may be constructing in the form of a short beam, which is rigidly clamped at one end; the load is applied at the free end. Alternatively, the load may be suspended from the load cell. Shear-type load cells in which the strain gauges are attached to the inner web of a short hollow beam measure shear force rather than bending moment.

Modern load cells are fast in response, robust, and tolerate considerable overloads. They are simple to attach, easy to protect against adverse environmental conditions, cheap and easy to maintain, and suitable for rapid and frequent auto-zeroing. They are, however, sensitive to vibration, although microprocessor-based damping and filtering devices can effectively counteract this.

A recent development is that of load cells which can be fitted to the forks of forklift trucks without interfering with their normal operation. This allows pallets to be weighed during handling.

5.12.2 Automatic Weighers

These fall into two main groups, namely, static and dynamic devices. Static weighing is used to checkweigh finished units or to weigh batches of ingredients, which are subsequently charged to the manufacturing process.

5.12.2.1 Checkweighing

Checkweighing involves the rapid weighing of individual units (200–300 per min). The items to be weighed must be correctly spaced (using photocells) and presented to the weighing head so as to avoid shock and vibration. The load cell readouts are fed to a microprocessor, which has been preprogrammed to execute a number of different functions. Thus, modern checkweighers automatically record totals of acceptable, overweight, and underweight items; display mean weights, standard deviations of weights, and weight change trends; reject underweight and overweight units; and provide feedback or activate filling or dispensing equipment.

5.12.2.2 Static Weighing

This usually involves fast feeding the bulk material into a tared vessel (the load cell having automatically weighed the empty vessel) until the required weight of material is approached, when the fast feed is automatically replaced by a fine feed device, which adjusts the batch to its target weight. Weighing vessels for static automatic batch weighing are usually supported on three points. For liquids or self-leveling solids, only one of these points needs to be a load cell. For other materials, three load cells may be employed; the microprocessor computes a mean weight.

5.12.2.3 Dynamic Weighing

This involves the assessment and control of a continuous flow of material. One such system measures the rate of loss of weight from a vessel containing material being charged continuously to a process. The vessel is suspended from a continuously transmitting load cell and is fed through a flexible gaiter. Feeding and discharge of the dispenser vessel is via a screw feeder.

Another form of dynamic weight control uses the belt weigher. In this, the material to be continuously weighed is fed at a controlled uniform depth on to a carefully mounted short section of belt passing over a servo-controlled zero-displacement weigh platform. The weigh signal is used to vary the belt speed and thus to control the weight delivered per unit time. Systems of this type are increasingly used in the dry blending of multicomponent ingredients. While considerable process flexibility is possible, continuous automatic weighing cannot yet match the accuracy of continuous batch weighers.

5.13 Factors Affecting Choice of Conveying System

5.13.1 Hygiene and Potential Contamination

Surfaces of conveyors, bins, pipeline, pumps, and so on come into direct contact with foods. Therefore, it is of great importance that hygienic aspects are properly considered when choosing food-handling equipment. This should be designed so that the accumulation of food debris is minimized and that there are no dead spaces where food residues can accumulate.

The equipment should be constructed from materials that are suitable for the purpose, do not in themselves pose a hazard to the product, and are easy to clean. In the EU, legislative requirements on the standards for machinery used for processing foodstuffs (EC 2006; Fraser 2010) require that:

1. The machinery should be designed to facilitate cleaning.
2. Surfaces and joints should be smooth, thereby eliminating the possibility of harboring organic material.
3. There should be minimal use of screws, rivets, edges, and recesses; cleaning residues should drain from equipment easily.
4. The design should prevent accumulation of organic material or infestation.
5. Lubricants should not come into contact with food.
6. Materials in contact with food should be nontoxic, non-tainting, and avoid the migration of hazardous materials into foods.

In addition, third-party auditing standards (BRC 2011; Kill 2012) require that all equipment in direct contact with food shall be suitable for food use and meet legal requirements. This does mean that factory management should retain evidence that such is the case, which may be produced during audits. In the case of new equipment, certificates provided by the equipment suppliers are acceptable. However, proving suitability is not so easy for existing, and especially old, equipment, but efforts should be made to produce some evidence that a risk assessment has been carried out.

The equipment must itself be of sound construction so that, as it wears, fragments do not contaminate product. For example, fabric- or plastic-coated belt conveyors often tend to fray along the edge. As a result, fragments can detach themselves from the belt and become mixed with the food product. Non-fraying belt is now available.

It is best to avoid painted surfaces where possible; paint is prone to flake off and thereby to give rise to a foreign-body hazard. The increasing use of stainless steel in the food industry has reduced the necessity for paintwork. However, where surfaces are painted, they should be of a nonfood color (e.g., dark blue) to highlight any food deposits on them. Moreover, any contamination from the equipment itself is more likely to be seen.

These issues are dealt with in some depth in Chap. 4.

5.13.2 Dust

Dust in any situation is undesirable but particularly so in the handling and movement of food materials. In the first place, food dusts encourage infection by microorganisms and infestation by insects, birds, and rodents. Secondly, dusts lead to cross contamination of foods by taints, odors, etc. Thirdly, food dusts are potential fire and explosion hazards. The United Kingdom Factory Inspectorate lists no fewer than 64 food materials, which have either caused dust explosions or else have been shown to be capable of doing so http://www.hse.gov.uk/food/dustexplosion.htm. Finally, dusts of any kind, if breathed by operatives, constitute a serious health hazard.

Care should be exercised in the selection and design of equipment for handling materials that are prone to generate dust. Obvious steps to consider include effective dust-proofing of conveying systems and the establishment of sparkproof conditions in high-risk areas. In the limit, it may be necessary to isolate particularly hazardous equipment such as high-speed bucket elevators and to fit explosion-venting devices as a safety precaution.

5.13.3 High- and Low-Temperature Handling

A considerable amount of conveying equipment must be capable of operating efficiently under high- or low-temperature conditions, or both. This is sometimes coupled with a requirement for complete immersion in liquids. Rubber belts are generally precluded from such applications, even though special types are made to withstand temperatures of about 112–150 °C. Use is therefore made of wire belt or steel-band conveyors or of the many types of handling equipment based on conveying chains. Selection is governed largely by the application, although wide overlapping occurs.

For example, wire-mesh belt conveyors are employed extensively in baking ovens and dryers, as are steel-band conveyors, the perforated band type being especially suited to drying applications. Stainless steel-band conveyors are used primarily in the processing and final stages of production, often in blast-freezing tunnels at temperatures of −40 °C and below. An interesting application here is in the continuous molding and freezing of ice cream at −45 °C. The blocks of ice cream are carried on stainless steel bands straight from the molding machines through the freezing chambers to the packing and dispatch departments.

Chain conveyors are used for work involving high and low temperatures, humid atmospheres, and complete immersion in liquids.

5.14 Transportation to and from the Factory

5.14.1 Loading Bays

The loading bay at the factory forms the interface between production and warehousing on the one hand and road or rail transportation on the other. It is therefore of vital importance that loading bay operations are efficient and do not cause bottlenecks.

Vehicle dimensions differ and the height of its load-bearing platform will fall as loading proceeds. Adjustable loading ramps or variable-height lifting platforms can form a bridge between the floor of the warehouse area and a covered trailer so that forklift trucks can load pallets directly into it. A large quantity of pallets may be loaded en masse on to a flat bed truck using a heavy-duty hoist fitted with multiple sets of lifting forks.

Flexible weather shields can be fitted to the loading bay doors to enable a truck to back into a hooded enclosure to give weather protection and pest proofing during the loading operation. This is especially important when loading chilled or frozen products into refrigerated vehicles in order to minimize heat gain.

As trucks should stand level during loading, attention should be given to the design of the apron on which they stand. Excessive slopes to accommodate drainage or storm water gullies directly under the wheels of a vehicle can tilt it. This may give rise both to loading problems and to difficulties in backing the vehicle close to the loading bay without hitting it.

5.14.2 Transportation of Foods

Control of conditions during transportation of food, either as raw materials or as packaged product, is a major factor affecting food quality. Ideally, control of environmental conditions, particularly for chilled and frozen products, should extend from production through to distribution and sale. Anything less than this “total” approach to environmental control may violate legal requirements and increases the risk of quality loss. Proper control of temperature, humidity, and sometimes the composition of the atmosphere surrounding the products is just as essential during transportation as it is during storage. Transport vehicles should therefore be suitably equipped to establish and maintain appropriate storage conditions under all foreseeable eventualities. If used to convey chilled foods or frozen goods, the vehicle should be precooled as onboard refrigeration equipment is usually designed only to offset external heat gain.

Goods in transit should be segregated to avoid cross contamination or tainting and should be stacked so as to allow good air circulation. Vehicles should be regularly cleaned and sanitized. Foods are particularly prone to damage during transportation. Moving equipment must therefore be designed to give the goods a smooth ride, restricting bumping damage and vibration. Because of its high frequency, the latter is particularly prone to causing damage. Distribution vehicles on multi-drop duties may be opened and closed up to 50 times per day. In these circumstances, transfers must be effected as rapidly and as hygienically as possible, and every effort must be made to minimize heat gain to the interior during the periods when the doors are open.

5.14.3 Refrigerated Transport

Refrigerated vehicles have a trailer with an integral refrigeration unit. Large trailers often have top-air delivery. The return air may be via the floor itself if it is of a T-bar design. Here the load is carried on the upper bar of T-section rails fitted along the length of the trailer, and the air moves in the spaces between them. Where the floor is not so configured, the food must be stacked on pallets. Alternatively, the air may be introduced via the T-bar floor and returned at the top of the vehicle. In either case, a loading pattern, which provides good air circulation, is essential. Temperatures should be monitored, preferably using recorders.

Containers onboard ship can also be refrigerated. There are two ways of doing this. One way is by employing a porthole system whereby chilled air is blown from a separate refrigeration system into a porthole near the base of an insulated container. The air then flows through the cargo space and leaves via a second porthole at the top of the container. The second way is to employ a container with an integral electrically driven mechanical refrigeration unit, which can be powered at depots or onboard ship. These mostly employ bottom-air delivery.

References

BRC (2011) British Retail Consortium, “BRC global standard for food safety, Issue 6”, effective date January 2012, TSO (The Stationary Office), London.

EC (2006) “Mechanical Engineering. Directive 2006/42/EC on Machinery.” http://ec.europa.eu/enterprise/sectors/mechanical/documents/legislation/machinery/

Fraser, I. (2010) (ed.) Guide to the application of the Machinery Directive 2006/42/EC, 2nd edit., European Commission—Enterprise and Industry, June, 404 pp. Available online at http://ec.europa.eu/enterprise/sectors/mechanical/files/machinery/guide-appl-2006-42-ec-2nd-201006_en.pdf.

Green, D.W and Perry, R.H. (2008a) (eds) “Perry’s chemical engineers’ handbook”, 8th edit., McGraw-Hill, New York, Section 10, pp.20–36.

Green, D.W and Perry, R.H. (2008b) (eds) “Perry’s chemical engineers’ handbook”, 8th edit., McGraw-Hill, New York, Section 8, pp.48–49.

ISO (2003) ISO Standard 6780 “Flat pallets for intercontinental materials handling—Principal dimensions and tolerances”, International Organization for Standardization, Geneva, 13 pp., http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=30524

Kill, R.C. (2012) “The BRC Global standard for food safety: A guide to a successful audit”, Wiley-Blackwell, Chichester, UK.

Wikipedia (2011): “Pallet”, http://en.wikipedia.org/wiki/Pallet.

Chapter 6
Productivity Issues: Industrial Engineering and Operations Management

A.A. Aly and C.G.J. Baker

6.1 Introduction

A food factory should be fit for the purpose for which it was designed. Thus, it should satisfy market needs for safe, good-quality products that enhance the profits of the company. Moreover, it should be capable of responding to changes in market demand that affect both product volume and mix. Meeting these fundamental requirements is aided by Industrial and Operations Management, which involves decision making in the design phase of the project, planning how to use the resulting facilities to meet the required demand, and optimizing production schedules. Of these three aspects, the first is clearly the most relevant to the present text; however, the other two should not be neglected.

Figure 6.1 illustrates the principal facets of Industrial and Operations Management that are of major importance in the design stage of the factory. As discussed in Sect. 6.2 below, the decision on where to locate the factory must be taken relatively early as this can have a major impact on the design. Plant capacity (Sect. 6.3) naturally has a significant effect on the profitability of the factory and should again be considered at an early stage. Product mix can also affect such factors as raw material inventories and downtime, which, in turn, also affect the cost of production. The specification and layout of process equipment and production lines (Sect. 6.4) not only have technical, quality, and food-safety implications but also affect operations and productivity. Section 6.5 discusses the adoption of lean manufacturing techniques. Although these can be expected to impact mainly on the day-to-day operation of the factory, they do need to be given consideration at the design stage. Finally, the specification and design of warehouses is outlined in Sect. 6.6.

A.A. Aly (✉)
Industrial and Management Systems Engineering Department, Kuwait University,
P.O. Box 5969 Safat, 13060 Kuwait
e-mail: a.aly@ku.edu.kw

C.G.J. Baker
Chemical Engineering Department, College of Engineering and Petroleum,
Kuwait University, P.O. Box 5969 Safat, 13060 Kuwait
e-mail: christophergj.baker@gmail.com

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_6,

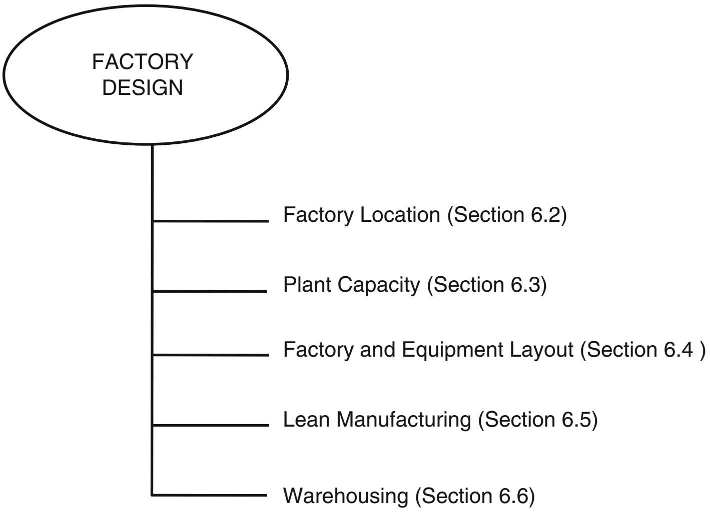


Fig. 6.1 Aspects of Industrial and Operations Management to be considered in the factory design

6.2 Factory Location

Selecting the most sensible location for a new food factory is a strategic decision, which may affect the technical and financial performance of the company for many years to come. It is not a straightforward task as it involves consideration of a number of constraints and both quantitative and qualitative factors. Some of these are listed in Table 6.1; others are discussed in Chap. 11. Simple comparative techniques can be used to identify the optimum location, for example, the analytical hierarchy process (AHP) devised by Saaty (1986). In this section, the principal factors affecting factory location are discussed.

6.2.1 Constraints

Before a possible site can receive serious consideration, it must satisfy the essential criteria listed in the first column of Table 6.1. The first of these, compliance with the strategic mission of the company, can encompass a number of factors. For example, how would it interrelate with other manufacturing facilities operated by the company? In many instances, the rational for building a new factory is to enable one or more older, less productive sites to be closed down. In this case, the new factory must be able to satisfy both existing markets and, if appropriate, develop new ones. Company strategy will also dictate the development of new products. The factory must be capable of delivering on both.

The location of the factory must be such that it is possible to expedite regular deliveries of the necessary raw materials and other goods and resources used in the manufacturing process (e.g., packaging materials) and to distribute the finished products within the desired market. Some factors entering into this decision include:

1. *Whether or not the raw materials are perishable*. Clearly, fruits, vegetables, dairy products, and other perishables need to be transported to the factory as rapidly as possible in order to maintain quality. In this case, it is desirable to site the factory close to the suppliers. Preprocessing some raw materials following harvesting can be used to maintain quality and therefore extend the permissible storage time and/or distance between the growing site and the factory. Examples include drying of grain, chilling of milk prior to and during transportation to the dairy, production

Table 6.1 Factors affecting new factory location

Constraints	Quantitative factors	Qualitative factors
• Compliance with strategic mission • Adequate and reliable supply of raw materials • Free access to markets • Compliance with zoning regulations • Availability of utilities • Availability of skilled labor • Availability of essential services	• Cost of land • Construction costs • Operating (production and transportation) costs • Financial incentives/packages • Tax (corporation, property, income) • Sales volume	• Quality of life of employees • Access to good educational and research institutions

of tomato paste from freshly picked tomatoes at the growing site, and freezing of freshly caught fish at sea in factory ships.

In the case of nonperishable raw materials, the distance between their source and the factory is obviously less critical than the cost of transportation and logistics (see below).

2. *Shelf-life of products*. In the case of short shelf-life products in particular, the distance (and hence time) between the factory and all envisaged markets is clearly a factor that needs to be taken into consideration. It is obviously less critical in the case of nonperishable goods.
3. *Transportation infrastructure*. This is another important factor that should be taken into account when selecting the factory site. In most cases, the principal requirement is the close proximity of major highways and/or rail networks. The absence of bottlenecks in the transportation infrastructure is important, particularly if just-in-time (JIT) manufacture is employed or the finished products have a short shelf life. It is also necessary to consider the impact that the resulting truck traffic will have on the local environment in the vicinity of the proposed factory, particularly if it is zoned as a mixed industrial and residential area.

In today's world, large quantities of fresh produce and processed foods are transported by air to distant markets. In these circumstances, proximity to local and international airports is an important consideration. Whether, in the light of global warming, this practice will continue on the same scale as today or will become prohibitively expensive due to the rising cost of fuel and the imposition of future carbon taxes remains to be seen.

In certain parts of the world (e.g., the Middle East), delivery of raw materials by sea is often essential. Examples include sheep and cattle from Australia and New Zealand for the manufacture of a variety of meat products and wheat for conversion into flour and subsequently baked goods. In these circumstances, regular and reliable shipping services and adequate raw materials storage are essential.

Other important factors that must be satisfied when deciding upon an acceptable location include the ready availability of skilled manpower, utilities, and essential services. Suitable provision must obviously be made to staff the new factory at all levels. It may be necessary to recruit senior management and technical specialists; alternatively, it may be possible to transfer existing staff to the new facility from elsewhere in the company. In either event, an attractive location will make this task easier. It is always desirable to hire production staff, fitters, office workers, etc., locally. The availability of a suitable pool of skilled manpower should therefore be confirmed before finalizing the location.

6.2.2 Quantitative Factors

Production costs may differ from one location to another and this should naturally be taken into account in choosing where to site the factory. It is therefore necessary to prepare estimates of the total production cost (C_{TP}) in, e.g., \$/y for each option that satisfies the constraints described above:

$$C_{\mathrm{TP}} = C_{\mathrm{M}} + C_{\mathrm{GE}} \tag{6.1}$$

Table 6.2 Breakdown of operating costs (Adapted from Peters et al. (2003))

Variable production costs

- Raw materials (food ingredients, including water if appropriate, process aids, food additives), including delivery costs
- Packaging materials (primary, secondary, and tertiary)
- Production labor (operators, fitters, etc., attached to production departments)
- Direct supervisory and clerical labor (attached to production departments)
- Utilities proportional to production (electricity, water, steam, natural gas, oil, process water, etc.)
- Waste treatment
- Inventory and warehousing costs
- Product distribution costs
- Maintenance and repairs carried out by engineering department
- Operating supplies (cleaning chemicals, PPE, etc.)
- Quality assurance/quality control laboratory
- Patents and royalties (if applicable)

Fixed costs

- Depreciation
- Local taxes
- Rent (if applicable)
- Insurance
- Financing charges (interest on capital)

Overhead charges

- General upkeep of the factory and surroundings
- Payroll overhead
- Medical services
- Staff restaurant and recreation facilities
- Factory contribution to corporate overheads

Administrative costs

- Executive salaries
- Clerical wages
- Legal fees
- Office supplies
- Communications

Distribution and selling (marketing) costs

- Sales office costs
- Advertising

Research and development

- Local product development
- Contribution to corporate R&D facility

Here C_{M} is the manufacturing cost and C_{GE} the general expenses. These costs can be divided into:

$$C_{\mathrm{M}} = Q \cdot C_{\mathrm{V}} + C_{\mathrm{F}} + C_{\mathrm{O}} \tag{6.2}$$

$$C_{\mathrm{GE}} = C_{\mathrm{A}} + C_{\mathrm{DS}} + C_{\mathrm{RD}} \tag{6.3}$$

where Q is the production rate (units/y), C_{V} the variable production costs ($/unit), C_{F} the fixed costs ($/y), C_{O} the factory overhead charges ($/y), C_{A} the administrative costs ($/y), C_{DS} the distribution and selling costs ($/y), and C_{RD} the research and development costs ($/y).

Table 6.2 gives a further breakdown of these costs, which are largely self-explanatory. The breakdown is for guidance only as different companies may choose to allocate their costs somewhat differently. For example, many organizations prefer their managers to take direct responsibility for as much of the cost base as possible, thereby minimizing the charges allocated to the overheads over which individual managers have little control.

The capital cost of the factory is reflected in the annual depreciation charges for buildings and equipment. For tax calculation purposes, there are legal constraints on the depreciation method that can be used. In the USA, for example, the normal technique is modified accelerated cost recovery system (MACRS), which accelerates depreciation charges in the early years of the planning horizon. However, for the purpose of comparing different options (e.g., factory locations), the simpler straight-line method is widely used.

The operating and transportation costs listed in Table 6.2 may well vary from one location to another. In particular, significant variations in wage rates, utility charges, local taxes, and insurance as well as transportation costs may well occur, especially if the sites being considered are in different countries. In order to evaluate this, a spreadsheet based on Table 6.2 should be constructed enabling each viable option to be compared. Construction of such a spreadsheet will require estimates of the rates of consumption of raw materials and utilities. The former is based on relatively simple material balances (see Chap. 2). Estimation of utility consumption is more complex. The construction of accurate figures for steam, natural gas, electricity, etc., requires detailed knowledge of the performance of each unit operation in the manufacturing process. In wet processes, usage of wash water in addition to process water should also be taken into account. The calculation of wages, salaries, and payroll taxes must obviously be built on accurate estimates of manpower requirements. Past experience with similar operations is naturally useful here. However, the more formalized techniques based on job design described in Chap. 4 of Vonderembse and White (1991a) can be used to provide more accurate estimates of the requirements.

In order to determine the preferred location, it is strictly necessary to compare the profitability of each option over its operating life. The annual profit P ($/y) is defined as the difference between the sales revenue and the total product cost in any given year:

$$P = Q \cdot C_s - C_{TP} \tag{6.4}$$

where C_s, selling price ($/unit). Note that production rates, revenue and costs, and hence profits can vary from year to year and also from one location to another. For example, higher manufacturing costs in one particular location could push the selling price higher and consequently reduce the market share. Moreover, long distances between the factory and viable demand centers may make significant inroads into such potential markets unrealistic.

The internal rate of return (IRR) i^* is the most reliable measure commonly employed to determine the profitability of a particular venture as it takes into account the time value of money. It is equal to the maximum rate of interest at which money can be borrowed to finance the project without making a loss. Full details of this approach are given in texts on engineering economy, e.g., Blank and Tarquin (2002) and Thuesen and Fabrycky (2001). It can reveal important differences between options that would not be apparent if more simplistic methods (e.g., payback period or capital recovery period) are employed that do not take into account the time value of money. The trial-and-error approach (Bisect Method) involves discounting the capital investments and annual profits over the life of the project to the initial starting time using different interest rates i. The sum of the discounted capital investments equals the sum of the discounted revenues when $i = i^*$. This approach will provide useful quantitative data that can ultimately be employed in conjunction with other relevant information to make the optimal choice of location. Note that if the highest calculated value of i^* is less than a minimum acceptable value set by the company, the minimum attractive rate of return (MARR), the best option would normally be not to invest in the new factory.

There is always an element of risk in estimating profitability, particularly in the case of projects having a long service life since even the most carefully calculated estimates are subject to uncertainty resulting from unpredicted future events. This should always be born in mind when comparing different locations, particularly when they are sited in different countries. In such cases, political upheavals, civil unrest, currency fluctuations, and changes in taxation legislation can all impact the calculations. Decision theory techniques, based on probability analysis, can be used to quantify risk; for details see Blank and Tarquin (2002) and Thuesen and Fabrycky (2001) cited above.

Many jurisdictions (countries, states, counties, etc.) offer financial incentives to encourage companies to move to their area. These may include direct grants, low-cost loans, reduced property taxes, and sometimes lower and/or deferred corporation taxes. These factors may all affect the profitability of the venture and need to be taken into account when making the final decision on the location.

Finally, after-tax profits are important to every organization, and the rates of corporation tax applying in the jurisdiction in which the factory is located will certainly need to be taken into account. If there are significant differences in these rates between possible candidate countries, this could have a major impact on the selection, as could any agreements that are in place to avoid double taxation.

6.2.3 Qualitative Factors

There will undoubtedly be a number of qualitative factors that may not directly affect the profitability of the venture but will have an impact on the selection of a suitable factory location. Most of these are quality-of-life issues that affect the ability of the company to attract and retain suitable staff. Examples may include availability and cost of housing; recreational, entertainment and educational facilities; commercial services such as banks, shopping centers, and car dealerships; and the proximity to major highways, airports, and other transportation hubs. These factors can be assessed for each location as follows:

1. List all qualitative factors i that are considered to be of importance and assign a relative weight W_i to each.
2. Assign a score $S_{i,j}$ for each of the factors i and locations j under consideration.
3. Sum the values of $S_{i,j}$ for each location j. Divide each result by the highest value and rank the results from highest to lowest.

6.2.4 Summary

To summarize, choosing an appropriate location for a new factory involves the following steps. First, the essential criteria discussed in Sect. 6.2.1 should be satisfied for each potentially acceptable location. This may well eliminate a number of proposed options. Secondly, the IRR for each of the remaining possibilities should be estimated to assess the financial feasibility of the venture. Where appropriate, possible risks should be factored in. Finally, any qualitative factors that might sway the balance between the leading options should be considered.

6.3 Plant Capacity

The capacity of a food factory (or production line) may be defined in several ways depending on circumstances. If the output is a single product, then the capacity of the factory or line may be defined as the maximum sustainable production that can be achieved in a specific unit time (shift, day, etc.) under normal operating conditions. However, if multiple products are produced, which is the normal case, then the definition becomes more complex as it depends on factors such as the product mix, the length of each production run, the downtime between successive production runs, and the layout configuration.

Specifying capacity is not as simple as it sounds. In this section, we will consider two distinct problems faced by companies building new food factories:

1. How do we define the design capacity of the factory under uncertain market conditions?
2. How do we adapt the production line to meet an increased future demand?

Of these, the first is more problematical as it involves an estimation not only of the initial sales volume but also of volume changes that may occur in the future. The second is relatively straightforward if the designer has past experience of operating similar equipment and production lines.

6.3.1 Specifying Initial and Future Design Capacity

6.3.1.1 Initial Capacity

Correctly specifying the capacity of a new food factory is fundamental to its economic success. If the designated capacity is too low, sales opportunities will be lost and competitors could be encouraged to move in to fill the gap. On the other hand, if it is too high, the factory will be underutilized; this will result in unnecessarily high depreciation and increase the fixed costs per unit of production. It is necessary to take into consideration not only the initial capacity of the factory but also changes that may occur in the foreseeable future. In other words, management must have a plan in place at the outset to accommodate future expansion should the need arise.

If the factory is to produce multiple products, the projected sales volumes of each must be specified as these will affect the nature and size of the process equipment, the size of raw materials and finished product warehouse facilities, and the materials handling and transportation infrastructure. These are several strategies for manufacturing multiple products (see Fig. 6.2). These include:

1. Option A. All products are manufactured on a single production line. This may or may not be possible depending on the nature of the products and required production volumes. Generally speaking, similar products (e.g., different varieties of canned fruit and vegetables, meat pies with different fillings, breakfast cereals with or without added dried fruit, and different flavors of ice cream) can in principle be manufactured on a single line provided an appropriate production schedule can be devised to meet the projected sales volumes.
2. Option B. Each product is manufactured on an individual production line. Although this is normally an expensive option, it may be justifiable for high production volumes or when the specific processing requirements of different products warrant it.
3. Option C. Hybrid systems in which two or more production lines share common items of equipment (e.g., freezers, dryers, or packaging machines). Although such arrangements can result in significant capital cost savings, they are likely to be the least flexible in their operation. This aspect must be thoroughly evaluated to determine whether this disadvantage outweighs any benefits.

Options A and C in particular require that an appropriate degree of flexibility be built into the system to meet fluctuations in production volumes and product mix. Where there is a choice between batch and continuous processing, batch (or semi-batch) operation provides the most flexibility. However, it may only be appropriate at relatively low production rates.

The initial design capacity is based on management's estimates of sales volumes at the time when the factory is scheduled to come on stream. As a useful rule of thumb, this initial capacity should not exceed 20–30 % of the market demand. Given the relatively short period between finalizing the design and commissioning the factory, it is probable that these estimates will be reasonably accurate. Obviously, internal factors such as phasing out existing capacity and moving it into the new facilities will also have to be taken into account.

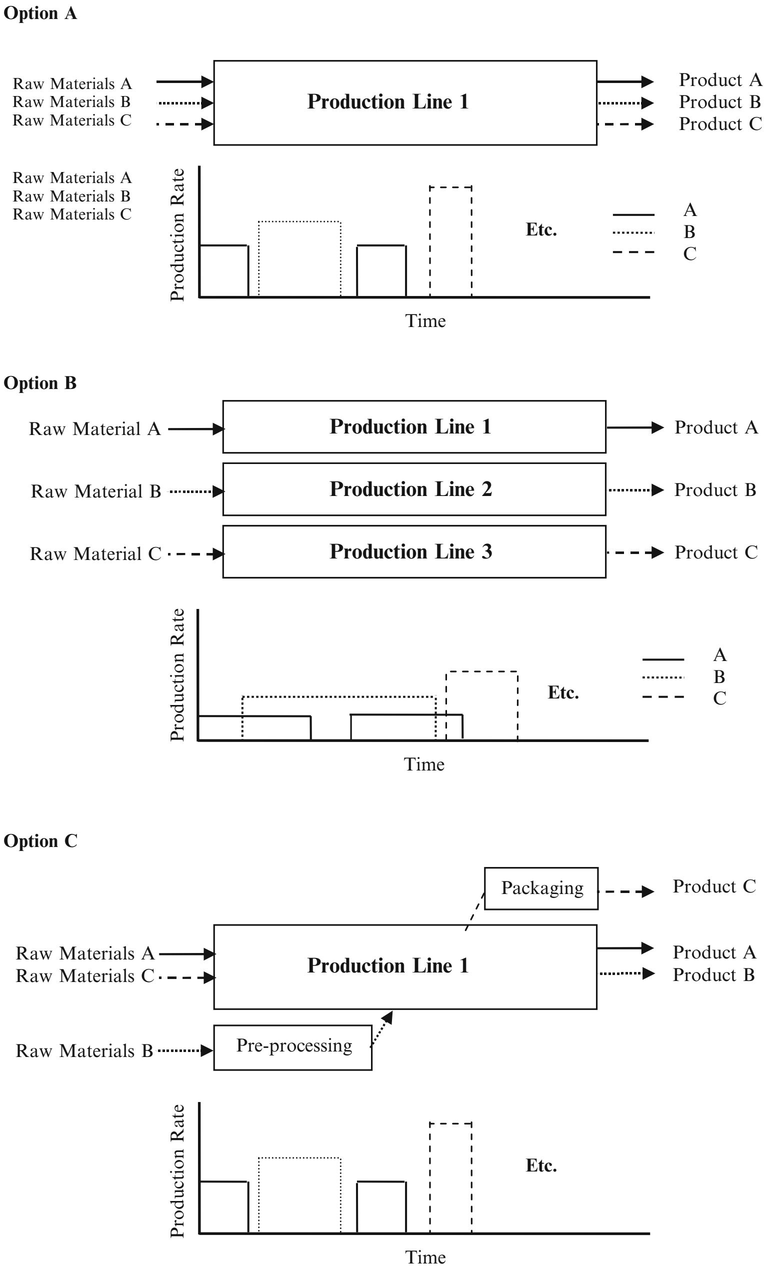


Fig. 6.2 Production line layouts

6.3.1.2 Future Capacity

As noted above, management should make provisions at the outset to accommodate possible future expansion should this be warranted by increased sales volumes. Possible strategies for accommodating this include the following alternatives:

1. Initially sizing the factory and equipment to accommodate all foreseen increases in production. In this case, experience has shown that the design capacity should not exceed 40–50 % of the foreseen market demand. This approach has both advantages and disadvantages. The principal

advantage is that increasing volumes can be managed smoothly at any time without disruption to the factory. There are, however, several disadvantages to this approach. The first is the inherent difficulty in predicting sales volumes several years in the future with any degree of certainty. Thus, the risk associated with this approach is relatively high. Secondly, having idle or underutilized equipment (and hence capital) tied up for several years before it is actually needed will reduce the IRR on the project and hence its viability. Finally, this approach will preclude the adoption of new technology should this become available during the life of the project.

2. Sizing the factory and equipment to meet the initial demand and delay the expansion until the time that it is needed, assuming that land and space are available. This approach eliminates all of the disadvantages cited above for the first option. However, it may cause disruption to production unless carefully planned and managed. More than one factory expansion can of course be accommodated if warranted by commercial considerations provided sufficient space is available on-site. If this approach is to be adopted, it may be prudent to initially oversize the factory building so that future expansions only involve the installation of new equipment.

In the final analysis, capacity decisions should be based on sound economics. As noted above, there is always some uncertainty in making predictions of sales volumes, raw materials and energy costs, product prices, etc., particularly in the longer term. Thus, it is advisable to use a probability-based approach to evaluate the different options available to the designer. Two such approaches, Monte Carlo simulation and decision trees, are commonly employed; in all but the simplest cases, both require that the problem be solved with the aid of suitable computer software. A knowledge of the following information is required:

1. The demand distribution—i.e., the relationship between the probability P_D that there is a specific demand D for the product in the marketplace and D.
2. The options available to meet demand D. Producing nothing should always be considered as a possible option.
3. The cost and revenue streams associated with each of the above options. Given the uncertainty in predicting future unit costs and income, these may also be expressed as probability distributions.

Monte Carlo simulation has been discussed in some detail in Chap. 10. Examples of the use of decision trees in capacity decisions are described by Vonderembse and White (1991b).

6.3.2 Adaptation of Production Lines to Meet Future Demand

A typical production line in a food factory consists of a number of independent operations, each of which serves a distinct function. Consider, for example, pasta production, which is illustrated schematically in Fig. 6.3. The raw materials are semolina (preferably from durum wheat) and water; the former is stored in flour silos before use. The semolina and water are first mixed under vacuum to produce a stiff air-free dough containing around 27–28 % moisture. This is then extruded, without expansion, into sheets or the traditional pasta shapes (spaghetti, macaroni, tagliatelle, etc.). Product variations are achieved by changing the die plate on the extruder. The raw pasta is then subjected to a gentle two-stage drying process in order to prevent cracking and then cooled. It is then packaged at around 12.5 % moisture and stored prior to dispatch.

In designing the pasta production line, each of the stages shown in Fig. 6.3 will normally be sized so as to accommodate the desired production rate. If, for example, this is 10 t/d, the extruder, dryers, and cooler and packaging machines should all be capable of handling this throughput. If one of the units, say the dryer, is only able to process, say 8 t/d, it is important to note that this will limit the total production of the line to 8 t/d. In this case, the dryer is said to be a *bottleneck*. If, on the other hand, the capacity of the dryer is 12 t/d, the total production rate will still be 10 t/d as the other units in the production line cannot handle the added capacity. In this case, the dryer is said to be underutilized.

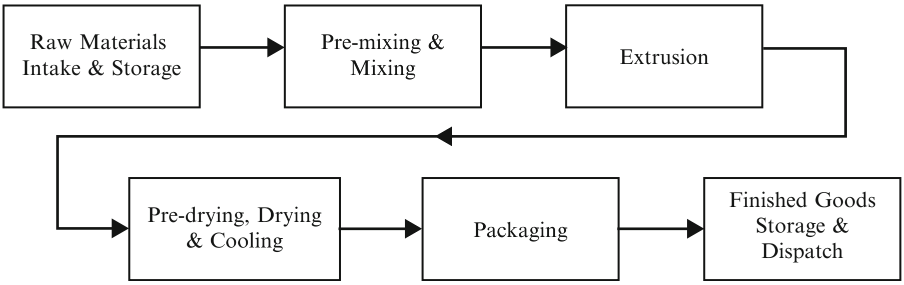


Fig. 6.3 Pasta production line

Careful consideration should also be given to the initial specification of utilities and services (gas, electricity, water, effluent treatment, etc.). It may well be advisable to allow for the maximum demands corresponding to the highest envisaged production rate at the outset as accommodating increased future supplies can be both disruptive and expensive.

The size of the flour silos will depend on the quantity of each batch of semolina delivered and the frequency of deliveries. For example, in the case of the 10 t/d production line operating 5 days per week, with weekly deliveries of semolina, a minimum storage capacity of about 60 t would be required. A similar calculation can also be undertaken to estimate the required finished goods storage area.

In the above example, let us assume that an increase in demand of around 20 % is envisaged from the beginning of year 4 onwards. How should this be accommodated? Several strategies may be considered, as described below.

1. Each unit is initially sized to handle 10 t/d. This will meet the production requirements of years 1–3. The added 2 t/d in year 4 onwards will be achieved by making the equipment work harder. This can be accomplished by a combination of the following methods:
   (a) Squeezing added production out of the line. Most items of equipment are deliberately oversized by the supplier in order to ensure that the process guarantees are met. Process engineering trials should demonstrate how this built-in additional capacity can be utilized.
   (b) Reducing the volumes of off-spec product (e.g., waste and rework) by improving quality and minimizing lost production due to breakdowns. It should be possible to identify the causes of off-spec production and implement measures to reduce it. Breakdowns can often be reduced by introducing a program of preventative maintenance.
   (c) Extending the production time by introducing overtime or an extra shift.
2. Some units are initially sized at 10 t/d and others at 12 t/d. Additional equipment is purchased and installed in time to achieve the added production from year 4 onwards. Choice of equipment to be initially sized at the higher throughput is based on the following considerations:
   (a) The incremental cost for a 12 t/d as opposed to a 10 t/d unit is relatively small.
   (b) The added cost of installing the additional equipment at the later date is relatively high.
   (c) Installation of the additional equipment at the later date would result in an unacceptable loss in production.
   (d) It is unlikely that there will be any major improvement in the technology during the intervening years. This is probably a reasonable assumption if this period is relatively short.

In the final analysis, the choice will ultimately be based on an economic analysis to determine the best possible option. This should factor in all the uncertainties. For example, quite different results may well result if the probability of requiring the added 2 t/d production is only 10 % as opposed to 90 %. The important thing to bear in mind is that the different options should be given due consideration during the design phase, along with what-if analyses for the various scenarios. This will provide management with a balanced view of all possibilities and the information needed to select the optimum choice within the constraints (e.g., limitations on capital spend) under which they have to operate.

6.4 Factory and Equipment Layouts

The layout of the factory and the equipment within it can have a major impact on manufacturing efficiency and costs. Vonderembse and White (1991c) cite a rather extreme example, which, although not related to the food industry, clearly illustrates the importance of this aspect of the design. The example compares vehicle-manufacturing plants operated by Jeep and Honda. Table 6.3 lists the principal features of these two facilities and illustrates the benefits of a modern custom-built plant.

Possible layouts are best evaluated using computer-aided layout packages, such as CRAFT, ALDEP and COFAD, which can be used to explore a large number of options at relatively low cost. These packages can be used not only to explore different equipment layouts but also to optimize the routing of service ducts, drainage channels, etc. The designs will also need to consider the movement of people, materials, and equipment within the factory that could give rise to food-safety risks associated with cross-contamination. Discrete-event simulation (DES) packages, also discussed in Chap. 10, are very useful in modeling material flows and identifying potential bottlenecks in the process.

The following example illustrates a commonly employed technique that could be used for designing the layout of a food factory. Consider a frozen pizza factory. Like many food manufacturing operations, this will have an essentially linear flow layout consisting of the following processing steps (these have been somewhat simplified in order to clarify the example):

1. Flour receiving and bulk storage
2. Other raw materials receiving and storage
3. Pizza base preparation (dough mixing, forming, and baking)
4. Pizza base storage
5. Preparation of toppings
6. Spreading topping on base
7. Chilling and freezing the assembled pizza
8. Packaging and palletizing
9. Frozen storage of packed frozen pizzas

Table 6.3 Comparison of two vehicle-manufacturing plants (Adapted from Vonderembse and White 1991c)

Feature	Jeep	Honda
Age of plant	Built early 1900s	Built around 1981
Floor space	5 million ft^2 (approximately 465,000 m^2)	1.7 million ft^2 (approximately 158,000 m^2)
Plant location	Inner city	Rural
Vehicle movement during manufacture	Vehicles wind up and down through most of the plant's sixty-plus buildings	Vehicles move in an orderly manner from the beginning to the end of the assembly line
JIT delivery of components	No	Yes
Production (vehicles/day)	750	875
No. of assembly workers	5,400	2,400
Productivity (vehicles per worker per day)	0.139	0.365

Fig. 6.4 Activity relationship matrix for frozen pizza manufacturing facility

	(9)	**(8)**	**(7)**	**(6)**	**(5)**	**(4)**	**(3)**	**(2)**	**(1)**
(1)	*U*	*U*	*U*	*U*	*U*	*U*	*O*	*U*	
(2)	*U*	*U*	*U*	*U*	*U*	*U*	*A*		
(3)	*U*	*U*	*U*	*U*	*E*	*A*			
(4)	*U*	*U*	*U*	*E*	*A*				
(5)	*U*	*U*	*I*	*A*					
(6)	*U*	*U*	*A*						
(7)	*U*	*A*							
(8)	*A*								

In order to produce an acceptable factory layout design, it is first necessary to consider the required proximity between the above processing steps (or departments as they are commonly referred to in Industrial and Operations Management terminology). These are defined by the following "closeness" indices: *A* is absolutely necessary, *E* is especially important, *I* is important, *O* is ordinary, *U* is unimportant, and *X* is undesirable.

It is first necessary to construct an activity relationship matrix, as shown in Fig. 6.4, which illustrates the required closeness of each of the departments listed above. For example, there is no need for Dept (1), "flour receiving and bulk storage," to be situated close to Depts (2) and (4)–(9). However, it should be reasonably close to Dept (3), "other raw materials receiving and storage." Likewise, it is absolutely necessary that Dept (3), "pizza base preparation," be situated close to Dept (4), "pizza base storage," and especially important that it be sited close to Dept (5), "preparation of toppings." All other spatial relationships for Dept (3) are unimportant.

Having defined the relationship matrix, the following procedure is adopted. The individual steps described below are illustrated in Fig. 6.5.

1. Select the first department; this will be placed at the center of the layout. The processing step with the greatest number of *A* relationships is selected. If more than one department has the same number of *A* relationships, a series of tie-breaking steps are then undertaken as follows. Among the tied steps, the one having the greatest number of *E* relationships is selected. If this fails, the numbers of *I* relationships are taken into consideration. If this does not break the tie, the department having the fewest number of *X* relationships is selected. Finally, if there is still a tie, one of the candidates is selected at random.

   In the example illustrated in Fig. 6.4, Depts (2)–(8) each have a single *A* relationship. It is therefore necessary to take the *E* relationships into account. Depts (3) and (4) are the only processing steps to have an *E* relationship and are consequently the only ones to remain in contention. Neither is associated with an *I* or an *X* relationship. Dept (4) is then selected at random.
2. The second department is then selected. This should have an *A* relationship with the first department selected and should have the maximum number of *A* relationships with the remaining departments. If there is a tie, the tie-breaking procedure described above should be employed.

   In the example, only Depts (3) and (5) have an *A* relationship with Dept (4). Both Depts (3) and (5) have a single *A* relationship with an unselected department: Dept (2) in the case of Dept (3)

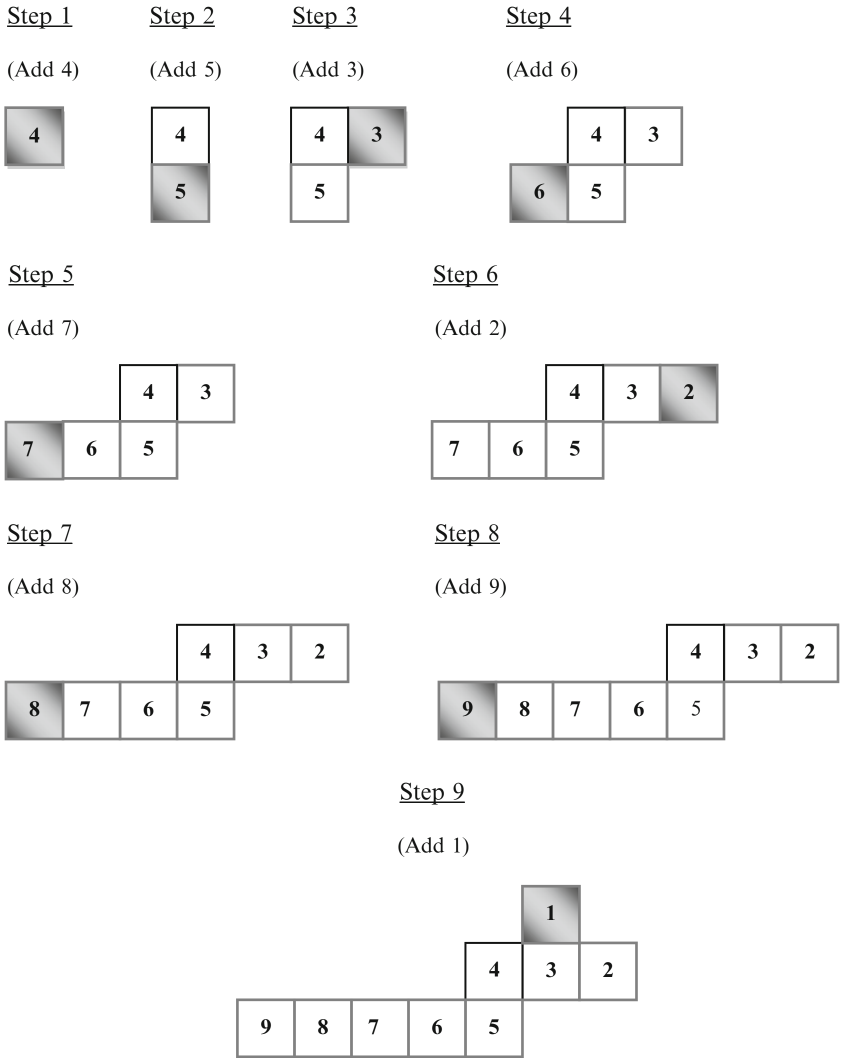


Fig. 6.5 Steps in the development of the frozen pizza factory layout derived from the activity matrix shown in Fig. 6.4

and Dept (6) in the case of Dept (5). As Dept (5) has an *I* relationship with Dept (7), it is selected in preference to Dept (3) and placed in the layout adjacent to Dept (4).

3. The third department to be incorporated into the layout should have the highest combined relationship with the two departments already selected. The following hierarchy is employed: *AA*, *AE*, AI, *A**, *EE*, *EI*, *E**, *II*, and *I**. Here, "*" denotes an *O* or a *U*. The selected department is located adjacent to the department(s) with which it has the strongest spatial relationship.

   In the example, Depts (3) and (6) have the highest combined relationship, *AE*, with Depts (4) and (5). Dept (3) is selected arbitrarily and is located adjacent to Dept (4) with which it has the *A* relationship.
4. The fourth department to be incorporated into the layout should have the highest combined relationship with the three departments already selected. The following hierarchy is employed: *AAA*, *AAE*, *AAI*, *AA**, *AEE*, *AEI*, *AE**, *A***, *EEE*, *EEI*, *EE**, *EII*, *EI**, *E***, *III*, *II**, and *I***. Again, "*" denotes an *O* or a *U*. The selected department is located adjacent to the department(s) with which it has the strongest spatial relationship.

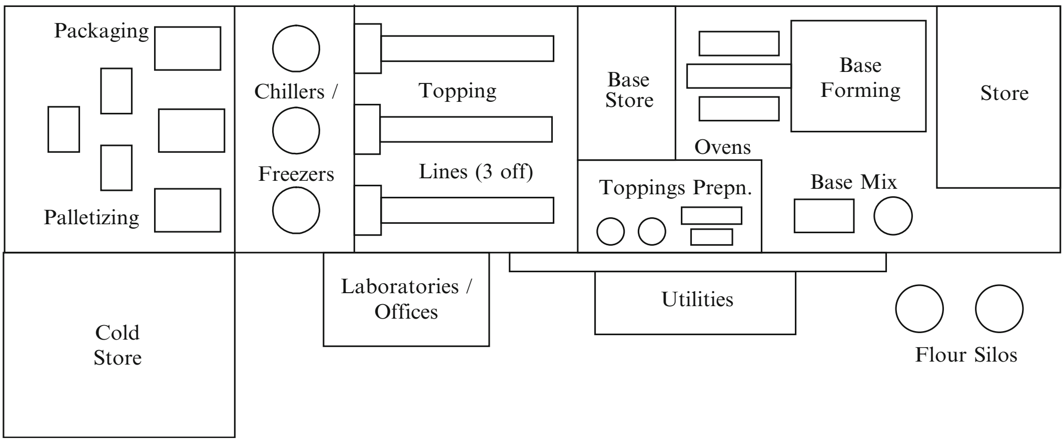


Fig. 6.6 Frozen pizza factory layout (Adapted from Wallin (1997))

Dept (6) exhibits the highest score in the example (*AE**) and is located adjacent to Dept (5) with which it has the *A* relationship.

5. Subsequent departments are selected in turn using the same logic as outlined above. The results for our example are as follows:
   - Dept (7) scored *AI*** and was located adjacent to Dept (6).
   - Depts (2) and (8) both scored *A*****. Dept (2) was chosen arbitrarily and was located adjacent to Dept (3) with which it had the *A* relationship.
   - Dept (8) scored *A****** and was located adjacent to Dept (7) with which it had the *A* relationship.
   - Dept (9) scored *A******* and was located adjacent to Dept (8) with which it had the *A* relationship.
   - Finally, Dept (1) was selected. It was located adjacent to Dept (3) with which it had a weak (*O*) spatial relationship.

The final layout depicted in step 9 of Fig. 6.5 is one of a number of possibilities that can be formulated on the basis of the relationships depicted in Fig. 6.4. In this instance, those tested all yielded broadly comparable results, which are quite similar to the layout of a frozen pizza factory (Fig. 6.6) described by Wallin (1997).

In order to convert the schematic layout shown in Fig. 6.5 into a finalized factory design, it is necessary to specify a number of other factors. Firstly, the floor areas required by each department (process step) must be known; these are largely dictated by the size and layout of the equipment within each department and the manpower space requirements. External facilities such as utility, office and recreational buildings, laboratories, and access roads must also be incorporated into the design.

In many cases, the footprint of a new food factory will be constrained by the area of the land upon which it is built. Although a single-story building is arguably best suited to many food-production processes, it may not be the best option in areas where high land prices prevail or where gravity feed of the raw materials is desirable. Under these conditions, a multistory factory could provide a better solution despite its higher per unit floor area building costs. The following guidelines will aid in the design of an effective factory layout (Wallin 1997).

1. The selected equipment layout should minimize the use of floor space. However, sufficient spacing should be allowed between individual items of equipment to permit efficient operation, manual intervention, routine maintenance, and effective materials handling.

2. In order to provide as much flexibility as possible to accommodate future changes, internal partitioning, columns, and drains should be kept to a practical minimum and service channels and ducts should be sited with this possibility in mind. Some internal partitioning may, however, be needed to accommodate food-safety requirements (see below). Land earmarked for the future construction of buildings and facilities required for factory expansion is normally grassed over and landscaped until required.
3. A straight-line arrangement with raw materials entering at one end and finished goods leaving at the other is normally the most desirable option. However, this is not always feasible as some processes require large amounts of work in process (WIP) and/or large equipment (e.g., baking ovens, chillers/freezers, and dryers), which would result in excessively long production lines. An example of an approximately linear design, that of a frozen pizza factory, is shown in Fig. 6.6. Note that in this example, spiral chillers and freezers are employed in order to minimize floor space and the length of the line.
4. Food-safety and processing requirements often dictate the need to partition off different areas of the factory. A commonly adopted approach is to separate high-risk from low-risk areas. High-risk operations include the storage of sensitive fresh ingredients, fresh food preparation, and the filling of foods into primary packaging. Secondary and tertiary packaging and the storage of frozen and ambient foods constitute low-risk operations. Typical examples of where to partition the factory include:

   - After filling or sealing the product in its primary packaging.
   - After cooling in a chilled or frozen food factory (as in the example in Fig. 6.6). In such cases, the chiller or freezer can act as the partition.
   - After drying in a dehydrated food plant; here the water activity will be too low for microbial growth to occur.

   It is also common practice to separate areas requiring different environments.

6.5 Lean Manufacturing

Day-to-day production scheduling is beyond the remit of this book. However, the designer of a food factory must be aware of how it is planned to manage the production operations as this can have a major impact on the design. As discussed by Tomkins et al. (1996a), there has been a progressive change in the philosophy and practice of manufacturing in general since the 1970s when traditional scheduling methods were employed. These were characterized by large inventories, small inventory turnovers, long production lead times, high manufacturing costs, poor quality, long delivery times, poor customer service, high space and storage requirements, high handling requirements, and low productivity. Since then, times have changed considerably and, in common with most industrial sectors, food manufacturing has had to adapt to this new environment. In most modern economies, a relatively small number of large supermarket chains dominate food retailing. As a result, they exert considerable pressure on manufacturers to produce an ever increasing number of product lines in a range of diverse packaging formats. Moreover, small batch sizes and short lead times are increasingly the norm. All these factors have forced food manufacturers to become more flexible and efficient. As a result, most have streamlined their operations through at least the partial introduction of techniques such as JIT, total quality management (TQM), total employee involvement (TEI), and computer integrated manufacturing systems (CIMS). As discussed below, many of the features of these techniques are incorporated into “lean manufacturing.”

6.5.1 Fundamentals

The philosophy underpinning lean manufacturing is the elimination of waste in all its forms. Stevenson and Jain (2005) have defined seven sources of waste:

- Overproduction—producing more product than is required to meet customer demand.
- Queuing—this can result from holdups in any phase of the manufacturing process because of a lack of materials or personnel or bad scheduling. It increases the quantity of WIP.
- Unnecessary movement of people or materials.
- Overprocessing—performing additional cosmetic operations that are not essential to satisfy demand.
- Inventory—excessive raw materials, WIP, or finished goods inventories.
- Nonconformity—production of out-of-spec product.
- Inefficiency—unnecessary waste of time, effort, materials, energy, or water; inefficient use of equipment.

Careful consideration of all these aspects at the design stage is essential in ensuring that the factory operates in the most efficient and profitable manner.

Stevenson and Jain (2005) stated that the most important source of waste is probably inventory. They considered excessive WIP to be "particularly wasteful as it hides operating problems and barriers to smooth flow (of both information and materials) throughout the business." JIT is a manufacturing philosophy that focuses on reducing inventory and hence reducing costs, improving quality, and shortening the time between ordering and delivery. Although few, if any, food manufacturers have fully achieved all the goals underlying JIT, some have made significant strides in this direction. The fundamental principle of JIT is that raw materials and other needed supplies are ordered only when and as required. This contrasts with traditional manufacturing methods in which relatively large stocks of these items are continuously built up and maintained. The JIT approach has a number of benefits. Firstly, and most obviously, it results in reduced feedstock, WIP, and finished product inventories and hence their associated carrying costs. Other benefits, described below, include the elimination, or at least significant reduction, of waste, lower storage and warehousing requirements, and improved relationships between the manufacturer and its employees, suppliers, and customers. However, one of the drawbacks of JIT is the need for suppliers to be located in close proximity to the manufacturing unit in order to minimize response time.

Traditional manufacturing is a "push" system in which product is manufactured according to a predetermined schedule based on current sales forecasts, transferred to a WIP or finished goods store, and subsequently transported to the customer when an order is received. In contrast, JIT is based on a "pull" system in which the production process is triggered by the receipt of an order from a customer and the consequent release of a "kanban" (Vonderembse and White 1991d).

Some specific benefits of JIT in food manufacturing operations are as follows:

1. Reduced production setup time. This is of growing importance in the food industry as manufacturers are under increasing pressure to move to flexible manufacturing systems in which batch sizes are reduced and the product mix is increased. Tomkins et al. (1996a) claimed that full implementation of JIT in discrete manufacturing operations can reduce the setup time by 75 %. However, this figure is very unlikely to be achieved in food manufacturing as few such operations are truly discrete and there are other constraints. From the design standpoint, Stevenson and Jain (2005) highlight the need to segregate all changeover activities.
2. Increased raw materials turnover and hence lower storage requirements. Even the partial introduction of JIT should result in a significant savings.
3. The establishment of ongoing waste-reduction programs in all areas, including raw materials, WIP, energy, water, and packaging.

4. The commitment of both management and staff to the introduction of JIT in all aspects of the business such as updating the accounting system and other performance measures so as to make them more appropriate to JIT.
5. The integration of suppliers and clustering them around the manufacturing hub is a very important feature of JIT. When JIT is fully implemented, the number of suppliers will lower than that employed in traditional manufacturing and their prices will be lower. Most of the suppliers will be self-certifying in terms of quality and their delivery performance will be much improved.
6. Preventative maintenance is also key to the successful implementation of JIT as it minimizes the occurrence of unplanned line stoppages.
7. The standardization of materials, packaging, machine components, procedures, etc., also results in more streamlined production and reduced costs.
8. TQM, combined with JIT education and training, and a culture of continuous improvement are also integral components of JIT.
9. The underlying philosophy of JIT manufacturing systems can result in shorter product development times.

6.5.2 Implementation

A number of papers that discuss the implementation of lean manufacturing techniques in the food industry have been published in the literature. Most relate to supply chains as opposed to food manufacturing in isolation. Vonderembse et al. (2006) distinguished between three possible supply chain designs, namely, lean, agile, and hybrid. Of these, the lean supply chain is most relevant to the needs of the food industry as it applies to standard products that have reasonably stable design and demand characteristics, which facilitate forecasting future demand, and production requirements that only change slowly over time. In contrast, the agile supply chain is best suited to maintaining a competitive advantage in global markets that are both rapidly changing and continually fragmenting. Finally, the hybrid supply chain was recommended for “assemble to order” products whose demand could be accurately forecast.

Fuentes-Pila et al. (2007) discussed the application of lean production methodologies and tools in a Spanish egg-producing company. The particular company studied was vertically integrated; it purchases flocks of one-day-old chicks, which are subsequently raised until they are transferred to a layer house, where they start to lay at 18–22 weeks of age. Eggs are moved by conveyor belts to the egg classification and packaging facility. The company also produces feed in its own feed mill ostensively following JIT principles. Its major customers are large retailers. The authors employed value stream mapping (VSM) to provide the company with a description of material and information flows of products and services from a supplier to a customer. This was employed to distinguish those processes that added value from those that did not. As a result of VSM, the company achieved a 30 % increase in productivity as a result of changing the product specifications and introducing new conveyor systems to handle the classified eggs. However, the authors concluded that it was much more difficult to apply lean principles to primary egg production as a pull system would require radical changes in the process.

Stevenson and Jain (2005) discussed the basics of lean manufacturing and its relevance to the food industry. Subsequently, Jain and Lyons (2009) studied the implementation of lean manufacturing in six UK food manufacturers producing a diverse range of products, namely, edible oil (Case 1), sliced meat (Case 2), biscuits (Case 3), snack foods (Case 4), tea bags (Case 5), and sandwiches (Case 6). Their objective was to determine the extent to which the industry had adopted these practices, which have proved so successful in the automobile industry in particular. The multifaceted approach employed in their case studies included completion of a questionnaire by the company, a plant

Table 6.4 The uptake of lean manufacturing practices by the UK food industry (Adapted from Jain and Lyons 2009)

Lean practice (number of sub-practices)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Percent uptake
Aligning production with demand (4)	0	0	0	0	0	3	12.5
Supplier integration (6)	1	3	2	2	5	3	44.4
Employee involvement and empowerment (7)	0	5	5	3	4	2	45.2
Elimination of waste (9)	5	8	4	4	6	6	61.1
Total (/26)	6	16	11	9	15	14	

visit, and interviews with key personnel—the plant manager, purchasing managers, operations managers, and logistics managers. The findings of the study, in condensed form, are summarized in Table 6.4. Each lean practice cited was broken down into a number of sub-practices in the paper. "Aligning production with demand," which is arguably the most important feature of lean manufacturing, had a particularly poor uptake. It was practiced only by the sandwich plant (Case 6), which did employ a manufacture-to-order (MTO) strategy because of the very short shelf life of the product. The principal reasons for not following this practice in other cases included wide demand variability, limited shelf life, the need to fulfill customers' orders rapidly from stock, variable raw material quality, and food-safety issues. Moreover, in Cases 1–5, the decoupling point at which it was necessary to differentiate between product variants occurred relatively late in the process. This enabled the factories to respond rapidly to customer requirements. In an environment in which the major issue is price, there has been little attempt by the manufacturers to integrate their operations with those of their suppliers. Involvement of the workforce in initiatives to improve production has been quite variable. For example, no employee involvement and empowerment measures were observed in Case 1, the edible oil plant. No reasons were given. In the remaining cases, fluctuations in production demand resulting in variable working hours and the use of temporary, unskilled labor in the assembly and packing stages were said to limit the value of this approach. In none of the companies included in the study were "continuous improvement" programs practiced. Finally, there was a reasonable uptake of waste-elimination measures. For example, all of the plants employed a quality system, standardized operations, and 5S, which encourages effective workplace organization (QualityTrainingPortal 2004). In four out of the six plants, statistical process control and preventative maintenance had also been adopted. However, significant losses were often incurred during process changeovers, which were normally lengthy and sequence dependent. Moreover, cleaning and sterilization were normally required before a new product could be produced. Frequent changes at the packaging stage were also limited by the need to avoid losses of packaging material. The sandwich plant (Case 6) was one exception; only 3 min was required to change from one type of sandwich to another and, typically, 120 changeovers were made per day.

6.5.3 Impact on Factory Design

It may be concluded that although certain aspects of lean manufacturing can be expected to play a significant role in the day-to-day operation of the food factory, they are unlikely to have a major impact on its design apart perhaps from warehousing specifications (see Sect. 6.6) and in certain cases the proximity to suppliers and markets. However, the design team should be aware of ongoing developments in this area and changes in the food chain that may impact on their work. In contrast to mainstream food processing, the benefits of lean manufacturing, and JIT in particular, have been reported to have resulted in significant benefits in the fast food business (Anon 2005) and retailing (Moore 2007).

6.6 Warehousing

6.6.1 The Role of Warehouses

As discussed in Sect. 6.5, one of the major impacts of the introduction, or partial introduction, of lean manufacturing is a reduction in warehousing requirements. In an ideal JIT world, there would be no need for warehouses, which not only increases costs but, in most cases, does not add value. In practice, however, there are many reasons why raw materials, in-process, and finished goods storage facilities cannot be eliminated. For example, many raw materials are seasonal in nature or have to be shipped in bulk over long distances. Jain and Lyons (2009) cite several such examples in their case studies:

- The edible oil plant purchases, e.g., 3,000–6,000 t shipments of crude palm oil from various locations around the globe, which it stores off-site.
- The sliced meat plant purchases raw meat during the lean season at a discount and stores it in the form of cooked or cured meat.
- The snack food plant imports a wide variety of nuts from around the globe and, on average, maintains an inventory of 3 weeks supply.
- The tea bag plant, which processes 80,000 kg of tea per day, has to maintain a large off-site storage facility as its suppliers are located some 3,000 miles away.

Clearly the requirements for each factory need to be assessed on an individual basis.

Tomkins et al. (1996b) defined the missions of a warehouse as follows: (1) to hold the inventory necessary to balance and buffer the variation between production schedules and demand and (2) to accommodate and consolidate products from various points of manufacture within a single firm, or from several firms, for combined shipment to common customers. They also noted that local warehouses may be spatially distributed to permit a rapid response to customer demand.

The need for in-process storage can be attributed to factors as diverse as poor factory management and essential quality requirements. For example, cheddar cheese needs to be stored at 4–8 °C for 6–12 months to enable it to mature. Certain alcoholic beverages also need to be stored under controlled conditions, sometimes for extensive periods, to allow their quality to develop fully. Positive release programs, in which raw materials, WIP, and finished goods (e.g., canned vegetables) are only allowed to proceed to the next production or distribution stage after they have passed the required quality assurance/control tests, are an important element in ensuring food safety.

Finally, a finished goods warehouse may facilitate efficient and cost-effective distribution of single or multiple products to a range of customers. Such warehouses may be associated with an individual factory or be centralized in order to serve the needs of a number of manufacturing facilities. By way of example (Constellation 2009), a state-of-the-art automated bottling plant and distribution warehouse costing around £100m was opened in Avonmouth, UK, in 2009. Serving around 15 % of the UKs total wine and alcohol market, the warehouse occupies 858,000 ft^2 and can hold 57 million bottles of wine. In order to reduce distribution costs and achieve significant environmental benefits, wine is shipped from Australia in 25,000 l vats and bottled on-site at the rate of 800 bottles per minute. Constellation Europe, which operates the facility, claims that the resulting energy savings are equivalent to 250,000 km travelled by heavy goods vehicles.

6.6.2 Receiving and Shipping Areas

When designing a food warehouse, it is necessary to consider not only the storage requirements but also the activities involved in receiving and shipping the materials. Tomkins et al. (1996b) listed the following steps involved in determining the total space requirements for receiving and shipping:

1. Determine what is to be received and shipped.
2. Determine the number and type of docks.
3. Determine the space requirements for the receiving and shipping area(s).

These activities have been described in depth by Tomkins et al. (1996b); the following paragraphs provide a summary of this material. Step 1 involves preparing data on the envisaged receiving and shipping activity, which will be used as a basis for the design of the new facility. It may be based on existing data, modified if necessary, for a similar warehouse. Alternatively, if this information is not available, it must be developed on the basis of a combination of past experience and envisaged market activity. In any event, the following information needs to be compiled for each receiving and shipping activity: (1) description of the load, (2) details of the unit loads (type, capacity, size, weight), (3) number of unit loads, (4) frequency of receipt/shipment, (5) nature of transport (mode, specification), and (6) material handling requirements (method, time). The number and type of docks (Step 2) is based on an analysis of the anticipated delivery and collection schedules. If the probabilities of these events are Poisson distributed and do not vary significantly with time, queuing theory (White et al. 1975) can be employed to determine the number of docks. Alternatively, DES is utilized. The dock configuration must then be designed. Since most deliveries and collections are made by road, dock design will be based on the envisaged flow of truck traffic around the site. The following factors should be considered:

- Access to the site should be designed to prevent trucks backing up on the highway.
- If access is from a narrow street, recessed or "Y" approaches should be employed.
- Service roads should be of adequate width (at least 12 ft per carriageway). If pedestrian walkways are to be provided, these should be 4 ft wide and physically separated from the carriageway. Gate openings should be at least 4 ft wider than the carriageway (6 ft wider if pedestrians will also use the gate).
- The radii of right-angle intersections should be at least 50 ft.
- If possible, traffic should circulate counterclockwise.
- Sufficient truck waiting areas should be located adjacent to the dock aprons.

Having completed the above analysis, it is necessary to determine the size and configuration of the docking areas. For food-safety reasons, the factory will in all likelihood have well-separated raw material and finished product storage facilities and hence docking areas. Figure 6.7 illustrates typical 90° and finger docks. The 90° docks require the largest apron depths "a" but the smallest bay widths "b." Tomkins et al. (1996b) tabulated values of required apron depth for a range of truck lengths (40–60 ft) and dock widths (10–14 ft). For example, in the case of a 10-ft 90° dock, "a" ranged between 15 and 20 % greater than the length of the truck. In all cases, it decreased somewhat with increasing dock width.

In addition to the docking, maneuvering, and truck parking areas, it is necessary to provide sufficient internal space within the warehouse to facilitate all the activities associated with receiving and shipping. These include (Tomkins et al. 1996b) restrooms, offices, material handling equipment maintenance, trash disposal, pallet and packaging material storage, truckers' lounge, buffer or staging area, and a sufficient area to facilitate maneuvering the materials-handling equipment. Tomkins et al. (1996b) discuss these requirements in some detail and present a worked example of their calculation.

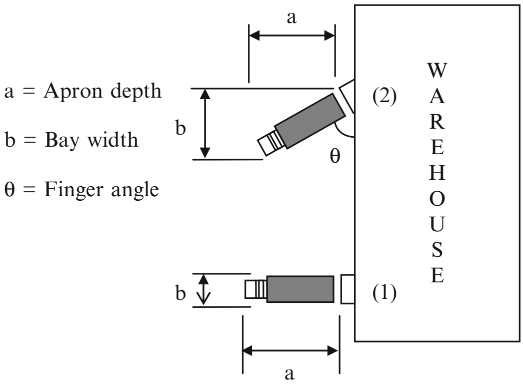


Fig. 6.7 Schematic illustrations of (1) a 90° dock and (2) a finger dock

6.6.3 Storage Requirements

When designing a food factory, it is necessary to consider the storage requirements for raw materials, finished goods, and occasionally WIP. The nature of these facilities depends on a number of factors:

- The characteristics of the raw materials/intermediate or finished products to be stored
- The quantities of material to be stored and the turnover rates
- Storage requirements (e.g., ambient, chilled, frozen, modified atmosphere)
- The method and frequency of delivery or shipment
- The method of conveyance within the factory

Major ingredients are often stored in bulk. Examples include powders such as sugar and flour, which are typically held in bulk storage silos having a capacity of 20 t or more to facilitate the delivery of complete tanker loads. Liquids such as edible oils and milk are usually stored on-site in large (up to 150,000 l) vertical stainless steel tanks. In either case, appropriate environmental control (e.g., of temperature and humidity) and conditions (e.g., air quality and flow, modified atmosphere) can be provided so as to maintain or develop the desired quality. Smaller quantities of minor ingredients are delivered and stored by the pallet load in a variety of packaging formats: sacks, drums, cases, large bags, etc. Certain ingredients (and products) need to be chilled or frozen during storage and shipping and, under these circumstances, suitable facilities also need to be provided.

Depending on requirements and costs, operation of the food warehouse can range from manual to fully automatic. In the former, fork lift trucks are used to move the pallets. In the latter, referred to as automated storage and retrieval systems (ASRS), high-speed stacker cranes are directed by computer to a specific location where they off-load or remove the pallet. Bar codes on the pallets are used to identify its contents and storage location.

Specifying raw materials and finished goods storage requirements is far from simple. The first step is to estimate the floor areas required on the basis of the following information, which needs to be compiled for each item stored: (1) description of the item, (2) details of the unit loads (type, capacity, size, weight), (3) quantity of unit loads stored (maximum, average, planned), and (4) storage space requirements (method, space standard, area, ceiling height required). In (4), the term space standard is the volume requirement per unit load stored. This includes the allocated space for aisles and honeycombing (wasted space that results when a partial row or stack cannot be used as this would cause blockage).

It is then necessary to design the storage layout for the warehouse(s). This is best achieved through the use of a scaled layout that includes all fixed obstacles such as columns, posts, stairs, doors, elevators, and plant services. Floor loading is a particularly important consideration in multistory facilities. As indicated by Tomkins et al. (1996b), the design should:

- Utilize the space effectively
- Provide efficient materials handling
- Minimize storage cost while providing the required level of service
- Provide maximum flexibility
- Facilitate good housekeeping

These requirements depend on a number of factors, some of which are of an operational nature. For example, the decision has to be taken as to whether dedicated or randomized storage should be employed. The former is intuitively preferable but the latter normally requires less storage slots.

According to Wallin (1997), warehouses are typically of low-cost construction. A racking system may act as the frame of the building, which can be either brick lined or just clad. Goods can normally be stored to a height of 18 in. below the trusses or sprinklers for ceiling heights of 15 ft or less or 36 in. below if the ceiling height is greater than 15 ft. A typical warehouse is 3–4 racks high, but some high-bay stores are 6–8 racks high. The height is limited by the stability of the racking system and the added costs of wind bracing and foundations. The modular construction of racking systems allows for their expansion in any horizontal direction or, if height permits, in a vertical direction as well.

Sufficiently wide aisles should be planned to permit due access to the stored goods and ease of materials handling. These should run parallel to the main spine of the building and lead to doors. Most goods should be stored along these aisles.

6.7 Conclusion

In this chapter, we have considered how the principles of Industrial and Operations Management can impact on the design of food factories. Specifically, the following topics were considered: factory location, design capacity, and allowance for future growth, equipment layout, the impact of lean manufacturing principles, and warehousing requirements.

References

Anon (2005) “McDonald’s, a guide to the benefits of JIT”, http://www.inventorymanagementreview.org/justintime/, dated 18 November.

Blank, L.T. and Tarquin, A. (2002) “Engineering economy”, 5th edit., McGraw-Hill, New York, 768 pp.

Constellation (2009) “Inside Bristol’s massive wine warehouse”, http://www.thisisbristol.co.uk/news/Inside-Bristol-s-massive-wine-warehouse/article-957142-detail/article.html, dated 2 May.

Fuentes-Pila, J., Rodriguez-Monroy, C., Antelo, R., Torrubiano, J. and Roldán, L. (2007) “Designing food supply chains: An application of lean manufacturing and lean supply chain paradigms to the Spanish egg industry”. Paper presented at the 1st International European Forum on Innovation and Systems Dynamics in Food Networks, Innsbruk-Igls, Austria, 15–17 November. http://ageconsearch.umn.edu/bitstream/6595/2/sp07fu01.pdf.

Jain, R. and Lyons, A.C. (2009) “The implementation of lean manufacturing in the UK food and drink industry”, International Journal of Services and Industrial Operations Management, 5(4), 548–573.

Moore, M. (2007) “Getting to the core—applying Lean in the food industry”, http://www.improvementandinnovation.com/features/articles/getting-core-applying-lean-food-industry, publ. 7 November.

QualityTrainingPortal (2004) Resource Engineering Inc, www.qualitytrainingportal.com/resources/5S/.

Saaty, T.L. (1986) “Axiom foundation of the analytic hierarchy process”, Management Science, 32, 841–855.

Stevenson, L. and Jain, R. (2005) “Lean manufacturing in the food industry”, Food Science and Technology, 19(3), 32–34.

Thuesen, G.J. and Fabrycky, W.J. (2001) “Engineering economy”, 9th edit., Prentice Hall, Englewood Cliffs, NJ, 637 pp.

Tomkins, J.A., White, J.A., Bozer, Y.A., Frazelle, E.H., Tanchoco, J.M.A. and Trevino, J. (1996a) “Manufacturing operations”, Chapter 10 in “Facilities planning”, 2nd edit., John Wiley and Sons, New York, pp. 451–493.

Tomkins, J.A.,White, J.A., Bozer, Y.A., Frazelle, E.H., Tanchoco, J.M.A. and Trevino, J. (1996b) “Warehouse operations”, Chapter 9 in “Facilities planning”, 2nd edit., John Wiley and Sons, New York, pp. 389–450.

Vonderembse, M.A. and White G.P. (1991a) “Job design and work measurement”, Chapter 9 in “Industrial operations management”, West Publishing, St Paul, MN, pp. 340–379.

Vonderembse, M.A. and White G.P. (1991b) “Capacity decisions”, Chapter 5 in “Industrial operations management”, West Publishing, St Paul, MN, pp. 160–203.

Vonderembse, M.A. and White G.P. (1991c) “Industrial operations management”, West Publishing, St Paul, MN, p. 288.

Vonderembse, M.A. and White G.P. (1991d) “Just-in-Time and synchronous operations”, Chapter 12 in “Industrial operations management”, West Publishing, St Paul, MN, pp. 474–516.

Vonderembse, M.A., Uppal, M., Huang, S.H. and Dismukes, J.P. (2006) “Designing supply chains: Towards theory development”, International Journal of Production Economics, 100, 223–238.

Wallin, P.J. (1997) “Food factory design and operation”, Chapter 17 in “Food industries manual”, 24th edit., (ed.) Ranken, M.D., Kill, R.C. and Baker, C.G.J., Blackie Academic and Professional, London.

White, J.A., Schmidt, J.W. and Bennett, G.K. (1975) “Analysis of queuing systems”, Academic Press, New York.

Chapter 7
Safety and Health

C.G.J. Baker

Abbreviations

AIHA	American Industrial Hygiene Association (USA)
BSI	British Standards Institute (UK)
COSHH	Control of Substances Hazardous to Health Regulations 2002 (UK)
DETR	Department of the Environment Trade and the Regions (UK)
EEA	European Economic Area
EHSR	Essential health and safety requirements
ESPE	Electrosensitive protective equipment
FDF	Food and Drink Federation (UK)
FIMA	Food Industry Medical Association (UK)
FLT	Forklift truck
HAZOP	Hazard and operability (study)
HSE	Health and Safety Executive (UK)
HGV	Heavy goods vehicle
OHS	Occupational health and safety
OSHA	Occupational Safety and Health Administration (USA)
OSHM	Occupational safety and health management (system)
PUWER	Provision and Use of Work Equipment Regulations 1998 (UK)
RIDDOR	Reporting of Injuries Diseases and Dangerous Occurrences Regulations 1995 (UK)
RSI	Repetitive strain injury
SHARP	Safety and Health Achievement Recognition Program (USA)
SMR	Supply of Machinery (Safety) Regulations 2008 (Amended 2011) (UK)
THOR	The Health Occupation Reporting Network (UK)
VPP	Voluntary Protection Program (USA)
WRULD	Work-related upper limb disorder

C.G.J. Baker (✉)
Chemical Engineering Department, College of Engineering and Petroleum,
Kuwait University, P.O. Box 5969 Safat, 13060 Kuwait
e-mail: christophergj.baker@gmail.com

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_7,

7.1 Introduction

A health and safety analysis should always be undertaken as part of the factory design as many potential problems can be recognized at the outset and eliminated before significant financial resources are committed to the project. This analysis will involve consideration of such fundamental aspects as factory layout, equipment specification, and inbuilt features such as proper ventilation. However, safeguarding the workforce will also depend on defining appropriate day-to-day operating procedures associated not only with production but also with maintenance, cleaning, and so on. Both aspects are considered in this chapter, although a greater emphasis is placed on the basic factory design and equipment specification issues. Food safety per se is not discussed.

Occupational health and safety issues have always been of major concern to governments and the general public alike as well as to factory management and employees. In most jurisdictions, they are the subject of large bodies of legislation, which are becoming increasingly stringent and complex year by year. Industrial accidents and ill-health are costly, not only to the individuals directly concerned, but also to the employer. HSE (2005) suggests that the cost of accidents to the latter could represent as much as 37 % of profits, 5 % of operating costs, or 36 times the insured costs. It is therefore to the benefit of all parties concerned to adopt and foster a work culture that encourages safe working practices.

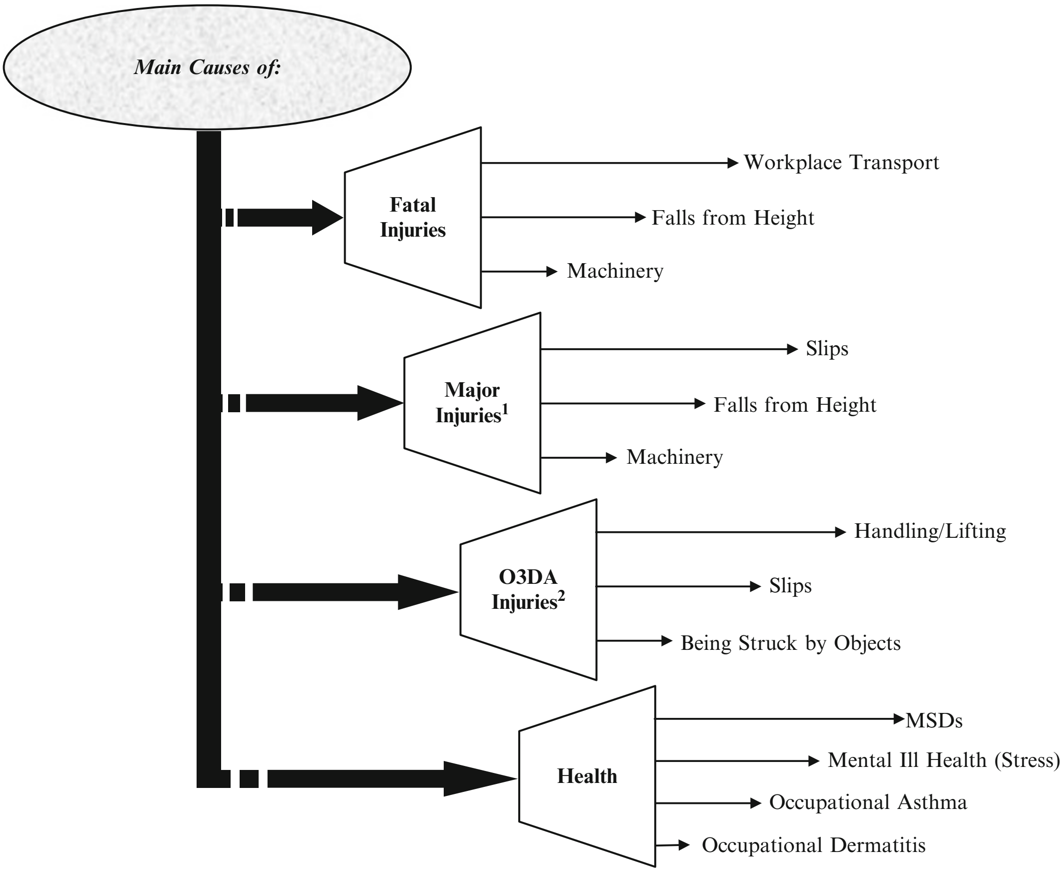
Food factories are regarded by many as being inherently safe working environments; however, this is far from the truth. As is discussed in Sect. 7.2, in comparison to other industry sectors, food manufacturing has a very poor safety record as exemplified by its high fatality and serious accident rates. The principal causes of these accidents, and techniques for reducing their incidence, are described in Sect. 7.3. Occupational health hazards are the subject of Sect. 7.4. Finally, risk assessment and the management of occupational health and safety systems are discussed in Sects. 7.5 and 7.6, respectively.

7.2 Accident Statistics in the Food and Drink Industry

Because manufactured food is inherently safe and wholesome to eat, it might be supposed that the factories in which it is produced are low risk in terms of health and safety. This is far from true since, by its very nature, food manufacturing involves a number of processing operations that are potentially hazardous. Although some companies have an excellent safety record, others perform relatively poorly in this respect. The UK's Health and Safety Executive (HSE) has published extensive material on the causes of occupational accidents and ill-health in the food and drink industries as well as in many other industrial sectors. Much of this information is available online through the HSE's Web site (http://www.hse.gov.uk), which provides a rich source of easily accessible information and advice.

HSE (2012) compares the 2009/2010 overall injury rates in the food and drink industry, 1,401 per 100,000 employees, with those in other sectors. This figure includes animal feed manufacture but excludes distribution, retail, and catering. By way of comparison, the corresponding rates for the construction industry, which is frequently considered to be particularly hazardous, and for the UK manufacturing industry as a whole were around 780 and 772, respectively.

The high accident rate in food and drinks manufacture in the UK back in 1990/1991 led the HSE to initiate discussions with the industry's umbrella organization, the Food and Drink Federation (FDF), and the principal trade unions involved. These discussions resulted in the initiation of the Recipe for Safety program, which set out to analyze the main causes of injuries and occupational ill-health



[1] Major injuries include hospitalization, serious fractures, amputations, etc., as defined in the Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1955. (RIDDOR 95)

[2] Over-3-day absence injuries

Fig. 7.1 Principal causes of accidents and occupational ill-health in food manufacturing in the UK (Adapted from HSE 2005)

(see Fig. 7.1) and to determine how they might be reduced (HSE 2011a). In 2004, the above organizations were joined by others to form the Food Manufacture Health and Safety Forum.

The success of the Recipe for Safety initiative has been very encouraging (HSE 2011b). Between 1990/1991 and 2009/2010, both the number of fatal injuries and the overall injury rate were approximately halved. In addition, there has been a 31 % reduction in the “major” injury rate since 1996 when RIDDOR (Reporting of Injuries, Diseases and Dangerous Occurrences Regulations) came into force—see RIDDOR (2012).

In a document entitled “Revitalising Health and Safety” (DETR/HSC 2000), the then UK government set out its targets for the following decade. These were:

- To reduce the number of working days lost per 100,000 workers from work-related injury and ill-health by 30 % by 2010
- To reduce the incidence rate of fatal and major injury accidents by 10 % by 2010
- To reduce the incidence rate of cases of work-related ill-health by 20 % by 2010
- To achieve half the improvement under each target by 2004

In order to achieve these targets, the government set out a 10-point strategy:

1. To promote better working environments. This would require a shift in focus from minimum standards to best practice, characterized by motivated workers and competent managers.
2. To recognize and promote the contribution to productivity and competitiveness of a workforce that is "happy, healthy, and here." Such a workforce understands its own responsibilities and benefits from a strong, healthy culture.
3. To ensure that occupational health remains a top priority. To this end, the Health and Safety Commission launched an occupational health strategy "Securing Health Together" (HSE 2000).
4. To positively engage small firms by promoting clear models of how they too can reap the benefits of effective health and safety management. This will be achieved by simplifying the law, without compromising standards, by ensuring that small firms are not deterred from seeking advice for fear of enforcement action, and by applying pressure through the supply chain.
5. To reform, where appropriate, the compensation, benefits, and insurance systems to motivate employers to improve their health and safety performance. These should secure a better balance in the distribution of costs of health and safety failures. Employers must also be motivated to rehabilitate injured workers so as to maximize their future employability.
6. To engrain more deeply a culture of self-regulation, particularly in the 3.7 million businesses with less than 250 employees. This should be achieved by demonstrating and promoting the business case for effective health and safety management, by providing financial incentives, and by changing the law to secure penalties that act as a deterrent. Health and safety management must be fully integrated within the general management system.
7. To encourage the fuller participation of workers in health and safety management as envisaged in the Health and Safety at Work etc. Act 1974.
8. To ensure that the government leads by example. Thus, all public sector bodies must demonstrate best practice in health and safety management and, moreover, promote best practice right through the supply chain.
9. To promote health and safety education at every level, starting in primary school. Most accidents are the result of poor management and ignorance of good practice rather than malicious intent. Coverage of risk issues in engineering, design, and general management education remains weak and needs to be strengthened.
10. The best way to protect workers' health and safety is to design it into processes and products. This approach should be encouraged through regulation and education.

The success of this approach can be judged by the statistics for 2010/2011 reported in HSE (2011c).

In the United States, OSHA (Occupational Safety and Health Administration) plays a similar role to the HSE in the UK. Its Web site www.osha.gov provides a useful entry point for obtaining guidance and statistical data. A selection of the sites of most relevance to the food industry is summarized in Table 7.1.

Statistics relating to occupational fatalities in the USA are presented in Table 7.2. In 2002, there were 64 fatalities in the food industry. Corresponding figures for the five previous years were of a similar magnitude: 57, 68, 83, 72, and 78. In contrast to the UK, the number of deaths in the food industry is significantly lower than that in the construction industry. The reasons for this are unknown. It could reflect different reporting procedures or real differences between the occupational safety and health performance of these two sectors in the two countries. In common with the US manufacturing industry as a whole, the principal causes of death in the food-manufacturing sector were "transportation incidents" and "contact with objects and equipment." Deaths resulting from "falls" appear to be less prevalent in the USA than in the UK.

Table 7.1 Selected OSHA Web sites

Topic	Last revised (as of 12 January 2012)	URL: www.osha.gov/ plus
Accident investigation	30 October 2006	SLTC/accidentinvestigation/index.html
Agricultural operations	22 January 2009	SLTC/agriculturaloperations/index.html
Ammonia refrigeration	26 August 2008	SLTC/ammoniarefrigeration/index.html
Beverage delivery—ergonomics	Not stated	SLTC/etools/beverage/index.html
Confined spaces	14 August 2007	SLTC/confinedspaces/index.html
Control of hazardous energy (lockout/tagout)	9 March 2007	SLTC/controlhazardousenergy/index.html
Crane, derrick, and hoist safety	15 May 2007	SLTC/cranehoistsafety/index.html
Dermal exposure	1 August 2008	SLTC/dermalexposure/index.html
Ergonomics	9 August 2007	SLTC/ergonomics/index.html
Fall protection	29 May 2008	SLTC/fallprotection/index.html
Fire safety	18 March 2009	SLTC/firesafety/index.html
Foodborne diseases	3 June 2005	SLTC/foodbornedisease/index.html
Grain handling	11 April 2011	SLTC/grainhandling/index.html
Grocery warehousing	Not stated	SLTC/etools/grocerywarehousing/index.html
Machine guarding	3 December 2007	SLTC/machineguarding/index.html
Meat packing industry	27 March 2007	SLTC/meatpacking/index.html
Molds and fungi	4 April 2008	SLTC/molds/index.html
Noise and hearing conservation	Not stated	SLTC/noisehearingconservation/index.html
Nonionizing radiation: radiofrequency and microwave radiation	4 May 2005	SLTC./radiofrequencyradiation/index.html
OSHA eTools and electronic products for compliance assistance	Not stated	dts/osta/oshasoft/index.html
OSHA publications, posters, and online order form	Not stated	pls/publications/pubindex.list
Poultry processing	31 July 2007	SLTC/poultryprocessing/index.html
Powered industrial trucks	13 November 2008	SLTC/poweredindustrialtrucks/index.html
Robotics	3 November 2008	SLTC/robotics/index.html
Small business	Not stated	dcsp/smallbusiness/index.html
Safety and health topics	Not stated	SLTC/index.html
Walking/working surfaces	15 May 2007	SLTC/walkingworkingsurfaces/index.html

US nonfatal injury and illness statistics for 2001 are given in Table 7.3. The incidence rates represent the number of injuries and illnesses per 100 full-time workers and were calculated as $(N/\mathrm{EH}) \times 200{,}000$. Here, N = number of injuries and illnesses and EH = total hours worked by all employees during the calendar year. The factor 200,000 is based on 100 full-time workers, each working 40 h/week, 50 weeks/year.

The statistics in Table 7.3 distinguish between cases of injury and illness and between incidents with and without lost workdays. No causal data are presented.

On all counts, the performance of the food-manufacturing sector was worse than that of the manufacturing industry as a whole and, with the exception of injuries and illnesses resulting in days away from work, worse than that of the construction industry. Data for meat products, dairy products, and beverages suggest that these subsectors had a somewhat poorer health and safety record than others in the industry.

More recent, but less detailed statistics have been presented by the US Bureau of Labor Statistics. BLS (2011a) gives details of injuries, illnesses, and fatalities in food manufacturing and BLS (2011b) presents preliminary data on fatal occupational injuries in 2010. In the latter case, no specific information on food manufacturing was presented.

Table 7.2 Occupational fatalities in the United States in 2002 (partial listing). *Source*—US Bureau of Labor Statistics

		Event or exposure (%)[a]					
Industry (or subsector)	Total fatalities (number)	Transportation incidents[b]	Assaults and violent acts[c]	Contact with objects and equipment	Falls	Exposure to harmful substances or environments	Fire and explosions
Total	5,524	43.1	15.2	15.8	12.9	9.7	3.0
Construction	1,121	26.3	2.9	18.2	33.0	17.5	2.1
Manufacturing	563	29.8	7.3	36.2	11.7	8.0	6.7
Services	680	39.0	24.7	9.7	11.5	12.2	2.5
Government	554	54.2	21.7	5.6	6.3	5.4	6.3
Food and kindred products							
Industry total	64	29.7	12.5	23.4	15.6	9.4	7.8
Meat products	13	23.1	23.1	–	–	–	–
Dairy products	5	–	–	–	–	–	–
Preserved fruits and vegetables	5	–	–	–	–	–	–
Grain mill products	13	–	–	46.2	–	–	–
Bakery products	6	66.7	–	–	–	–	–
Fats and oils	5	–	–	–	–	–	–
Beverages	6	50.0	–	–	–	–	–
Miscellaneous	10	40.0	–	–	–	–	–

[a] Based on the 1992 BLS Occupational Injury and Illness Classification Manual
[b] Includes highway, non-highway, air, water, and rail fatalities
[c] Includes violence by persons, self-inflicted injury, and assaults by animals

As well as describing its mission, vision, and challenges, OSHA's Strategic Management Plan for 2003–2008 (OSHA 2003) presented specific improvement targets for the 5-year period, which were in line with the US Department of Labor requirements. These were:

1. By 2008, to reduce the rate of workplace fatalities by 15 %
2. By 2008, to reduce the rate of workplace injuries and illnesses by 20 %

In order to achieve these targets, three specific supporting goals were set out. These were the following: reducing occupational hazards through direct intervention (i.e., enforcement); promoting a safety and health culture through compliance assistance, cooperative programs, and strong leadership; and maximizing OSHA effectiveness and efficiency by strengthening its capabilities and infrastructure.

It is worthy of note that OSHA runs a number of collaborative and training programs designed to improve standards of safety and health in industry. The Strategic Plan recognizes the importance of these programs and seeks to expand them. Details of the OSHA Voluntary Protection Program (VPP), Partnerships, and Safety and Health Achievement Recognition Program (SHARP) are accessible through OSHA (2012).

7.3 Specific Causes of Accidents in the Food Industry

Figure 7.1 identifies the most common causes of fatalities, injuries, and occupational ill-health in the UK food and drink industry. Where possible, the most effective method of reducing these hazards is to eliminate the causes from the outset, in other words to design out the problems. However, in many

Table 7.3 Incidence rates[a] of nonfatal occupational injuries in the United States in 2001 (partial listing). *Source*—US Bureau of Labor Statistics

	Injuries and illnesses				Injuries			
		Lost workday cases				Lost workday cases		
Industry (or subsector)	Total cases	Total[b]	With days away from work[c]	Cases without lost workdays	Total cases	Total[b]	With days away from work[c]	Cases without lost workdays
Private industry	5.7	2.8	1.7	2.9	5.4	2.6	1.6	2.7
Construction	7.9	4.0	3.0	3.9	7.8	3.9	3.0	3.9
Manufacturing	8.1	4.1	1.8	4.0	7.0	3.6	1.7	3.4
Services	4.6	2.2	1.3	2.5	4.4	2.1	1.2	2.3
Government	Not stated							
Food and kindred products								
Industry total	10.9	6.3	2.3	4.6	9.0	5.2	2.1	3.8
Meat products	14.7	8.5	1.6	6.2	10.0	5.7	1.4	4.3
Dairy products	11.8	6.9	3.9	4.9	11.2	6.6	3.8	4.6
Preserved fruits and vegetables	7.9	4.5	1.8	3.4	7.3	4.1	1.6	3.2
Grain mill products	7.6	3.8	2.1	3.8	7.2	3.7	2.0	3.6
Bakery products	9.0	5.7	2.3	3.3	8.2	5.3	2.2	2.9
Sugar and confectionery products	8.7	4.8	1.9	3.9	8.1	4.5	1.8	3.6
Fats and oils	8.6	5.8	2.6	2.9	8.4	5.6	2.4	2.8
Beverages	11.4	6.5	3.5	4.9	11.1	6.4	3.5	4.7
Miscellaneous	7.5	4.4	2.4	3.1	6.9	4.0	2.2	2.9

[a] The number of injuries and illnesses per 100 full-time workers. See text for calculation method

[b] Total lost workday cases involve days away from work, days of restricted work activity, or both

[c] Days-away-from-work cases include those which result in days away from work with or without restricted work activity

cases, this approach will not be completely practical and prevention will rely on operational and behavioral as well as design considerations.

In this section, techniques for reducing fatalities, injuries, and occupational ill-health are discussed. Particular emphasis is placed on factory design issues.

7.3.1 Workplace Transport

Workplace transport-related accidents are the single major cause of fatalities in the UK food industry. They account for around 38 % of deaths in the sector (HSE 2005). Principal causes highlighted were the use of lift trucks and HGVs.

HSE (2013a) gives extensive guidance on how to minimize the risk of accidents involving vehicles in and around the factory, and the reader is referred to this publication for detailed recommendations, particularly those relating to operational issues, which are not covered in depth in this chapter. The following were highlighted as priority areas: pedestrian safety and pedestrian/vehicle segregation, vehicle reversing, and falls from vehicles. Aspects of these hazards that are best considered at the factory design stage are discussed below. HSE (1999) poses the following questions:

1. *Pedestrian safety and pedestrian/vehicle segregation*

    (a) Have safe traffic routes been planned—preferably with one-way systems and, if needed, pedestrian crossing points?

- (b) Are vehicles and pedestrians kept safely apart both outside and, where possible, inside buildings?
- (c) Do vehicles and pedestrians have separate doors into buildings with suitable barriers where required?
- (d) Are appropriate speed limits enforced and, where required, speed bumps installed?
- (e) Are adequate signs in place, indicating, e.g., direction, speed limit, and no entry, and mirrors fitted on blind corners?
- (f) Are vehicles, including private cars, parked in designated areas?
- (g) Is access to loading yards restricted to essential personnel and are they wearing high visibility clothing where necessary?

2. *Vehicle reversing*
    - (a) Can reversing be eliminated or at least reduced, for example, by one-way systems?
    - (b) Do vehicles have adequate all round visibility? Are mirrors or other visibility devices fitted?
    - (c) Is there need to mark "reversing areas" so these are clear to drivers and pedestrians?
    - (d) Is there a need for a signaller (banksman) to direct reversing vehicles? Does the banksman have somewhere safe to stand?
    - (e) Do vehicles need to have reversing alarms fitted?
3. *Falls from vehicles*
    - (a) On FLTs, are makeshift platforms (e.g., pallets) used to raise workers on the forks? Deaths regularly result from this unsafe practice. It is a legal requirement that only properly constructed cages are used—designed especially for lifting persons.
    - (b) On grain vehicles, has the need to go on top been eliminated, for example, by fitting controls at ground level, providing ground operated manual or powered sheeting systems, etc.?
    - (c) On grain vehicles where access to view the top is still essential, are safe access arrangements in place, for example, a front platform fitted with a handrail and secure access ladder?
    - (d) On tankers, has the need to go on top been eliminated, for example, by "bottom filling," and fitting level gauges and controls at ground level?
    - (e) On tankers where access to manlids is required, are access arrangements safe? See HSE (1999) for suggested options.
    - (f) For both grain vehicles and tankers, can a gantry be provided at permanent loading stations to avoid the need to climb on top of vehicles?
    - (g) On flat bed vehicles, can loading/unloading/sheeting be done without getting onto the vehicle? For example, by using FLTs to put the load on and take it off the vehicle, and using sheeting gantries.
    - (h) On flat bed vehicles where access onto the vehicle is required, can this be achieved from loading bays to stop injuries while ascending/descending?
    - (i) On all vehicles, are access to cab arrangements well designed with suitable slip-resistant steps and handholds?
    - (j) On refrigerated vehicles, is access to controls and instruments possible without ascending ladders?

Other hazards specific to the food industry that have resulted in fatalities are also addressed in HSE (1999). These include overturning of tipping lorries and trailers, tailgate safety on bulk delivery vehicles, and FLTs falling from loading bays. Although some vehicle design issues are addressed, most suggestions relate to operational issues including, in particular, training.

Thus a safety audit carried out at the design stage is fundamental to the safe operation of the future factory. It should consider, in particular, the layout of vehicular routes and pedestrian walkways. Where possible, these should be separated. The types of vehicle using the site, desirable safety features, and requirements for the safe operation of these vehicles, including loading and unloading facilities, should also be considered in this audit.

Table 7.4 Falls from height: analysis of places from which employees fell (after HSE 2013b)

Fell from	Percent of falls	On vehicles, fell from	Percent of falls
Ladders	40	Back of truck (e.g., off flat bed)	35
Vehicles/FLTs	17	FLT forks	31
Machinery/plant	10	Cab steps	13
Platforms	10	Top of vehicle	9
Stairs	8	Tanker steps	4
Roof/false ceiling	7	Other	8
Scaffold/gantry	4		
Warehouse racking	4		

7.3.2 Falls from Height

Falls from height account for a relatively large number of fatalities and major injury accidents investigated by the HSE (HSE 2013b). Such falls:

- Are a major cause of fatal injury (20 %)
- Result in around 80 major injuries per year
- Result in an additional 230 over 3-day absences each year
- Can result in serious or even fatal injury even when the fall is less than 2 m

Table 7.4 summarizes the results of an analysis by the HSE of places from which employees fell. Activities being carried out by at the time included:

- Cleaning or maintenance (from scaffolding/gantries, ladders, roofs, or false ceilings)
- Loading/unloading (from road transport vehicles)
- Gaining access to high areas to, e.g., change light fittings or clean/maintain plant (from FLTs where the worker was standing either on the forks or on a pallet mounted on the forks)
- Cleaning, maintenance, or sampling (from machinery/plant)
- Retrieving goods from high level (from racking)

HSE (2001a) makes the following food-industry-specific recommendations to prevent falls from height:

1. *Cleaning*
   (a) Reduce cleaning at high level by alteration, modification, or maintenance of plant, for example, by ensuring effective extraction of dust and fumes.
   (b) Modify high structures to reduce ledges and surfaces where dust can accumulate.
   (c) Clean high structures from ground level, for example, with a foam jet cleaner.
   (d) Where high access is required, ensure that a safe system of work is used. This will include provision of safe access systems, such as mobile scaffolds, which are constructed and used properly.
   (e) Consider less common types of proprietary access equipment, such as inflatable platforms for silo cleaning.
2. *Sampling or checking*
   (a) Change sampling or checking procedures so they can be carried out remotely from floor level.
   (b) Relocate gauges and other equipment for measuring/monitoring/control to ground level.
   (c) Sampling or checking is likely to be a regular feature of production. As such, where high access is required, permanent access steps/platforms should be provided, along with adequate handrails.

3. *Maintenance*
    (a) Where frequent high-level access is required to equipment or machinery, ensure that permanent access steps, ladders, handrails, etc., are provided.
    (b) Where high-level access to plant, equipment or machinery is only required occasionally, ensure that safe access systems are employed, e.g., properly constructed and used mobile scaffolds.
    (c) Ensure that workers do not use FLT forks, or a pallet mounted on the forks, as a quick lift. Only properly constructed, fork-mounted cages should be used, as described in HSE (2013f).
4. *Falls caused by slipping*
    (a) A good cleaning regime is essential on surfaces and equipment from which people might fall.
    (b) Appropriate slip-resistant footwear is also required. Heeled footwear should be used on ladders.
    (c) One-third of over-3-day absence injuries caused by falling in the food and drink industry occur on stairs. This is often due to stairs becoming slippery as a result of contamination with food product or water. Appropriate cleaning regimes and suitable footwear are therefore necessary requirements.

    For further guidance on preventing accidents resulting from slips and trips, see Sect. 7.3.4.

HSE (2001a) also describes the circumstances surrounding a number of typical fatal and nonfatal accidents involving falls from height. A useful bibliography provides the reader with supplementary reading material. It is noted that in 50 % of cases where a person falls from height, safe access has not been provided. Risk assessments for both capital and project plans should therefore include consideration of this possibility and the provision of safe, permanent access, or suitable portable equipment. Retrospective provision of access systems, even portable ones, is more difficult to achieve.

7.3.3 Machinery

In recent years, accidents involving machinery have surpassed entry into silos as the third major cause of accidents in the food industry. Of the wide range of machines employed in the industry, conveyors, forklift trucks, and packaging machinery (particularly thermoform, fill, and seal machines, preformed rigid container packaging machines, and palletizers/depalletizers) are the most prone to accidents. In certain sectors, such as meat and fish processing, band saw accidents are relatively frequent.

Within many countries, the required health and safety standards of both new and existing equipment is strictly regulated under law. By way of example, we will consider the current situation in the UK as described by the HSE in several publications. In this country, all new machines, including own-builds, substantially refurbished machines from within the European Economic Area (EEA), and second-hand machines from outside the EEA should comply with the relevant "essential health and safety requirements" (EHSRs) of appropriate European Directives. These are:

- The Machinery Directive, implemented in the UK by the Supply of Machinery (Safety) Regulations 2008, which came fully into force on 29 December 2009 (Regulations 2008). The 2008 Regulation were subsequently amended in 2011.
- The Low Voltage Directive, implemented in the UK by the Electrical Equipment (Safety) Regulations 1994, which came fully into force on 1 January 1997 (Regulations 1994)
- The Electromagnetic Compatibility Directive, implemented in the UK by the Electromagnetic Compatibility Regulations 2006, which came fully into force on 28 June 2006 (Regulations 2006)

Table 7.5 Hazards of a general nature associated with food packaging equipment (after HSE 2001d)

Hazard	Nature of hazard	Safeguarding measures
Electrical	Ingress of liquid causing electrical shorting	Electrical equipment should have the minimum ingress protection (IP) specified in BS EN 60529: 1992. Control gear—IP 54, control devices—IP 55. If devices may be cleaned by water—IP 65
Thermal	Burns to operators	Surfaces that reach a temperature of 65 °C or greater should be insulated
Noise	Hearing impairment	Reduce by good design to the lowest possible level commensurate with the current state of the art
Radiation	Exposure to ionizing radiation from inspection devices and nonionizing radiation from etching/coding devices	Reduce to a level such that devices can be assigned to Category 0 or 1 as defined in clause 7 and Annex D of EN 12198-1: 2000
Chemicals	Various—depends on the nature of the chemical	Good design and compliance with the Control of Substances Hazardous to Health Regulations 1998 (COSHH)

A number of European standards have also been drafted to guide machine suppliers and users on how to meet the EHSRs. Purchasers can ensure that new equipment meets these requirements by specifying in purchase contracts that the equipment should comply with the relevant standards and then by checking on delivery that the Declaration of Conformity confirms this. HSE (2011d) provides food manufacturers with much useful advice relating to the purchase of equipment.

Machinery that complies with relevant Directives is CE marked. However, users should not automatically assume that it is therefore inherently safe; they should check for themselves that all relevant EHSRs are met.

In addition to the above requirements, the Provision and Use of Work Equipment Regulations 1998 (PUWER 2011) imposes duties on employers to ensure that work equipment is:

- Suitable for the purpose for which it is used
- Maintained in an efficient state, in efficient working order, and in good repair
- Safe to use and able to be safely cleaned and maintained
- If new, able to meet the requirements of SMR

Users should use the safeguarding options for new equipment as a benchmark for existing machines. Where the standard of safeguarding is found to be lower than for new machines, a risk assessment should be carried out to see if the safety features can be upgraded without making production and maintenance tasks unduly more difficult. Improvements may also be needed in basic hardware, systems of work, training, and supervisory procedures. All improvements should form an integrated package.

It is clearly not possible here to describe the safety aspects of each type of machine used in the industry. Consequently, discussion is limited to conveyors and the three types of packaging machine listed above (forklift trucks were considered in Sects. 7.3.1 and 7.3.2). In addition to the specific hazards associated with each individual machine, hazards of a more general nature should also be considered. By way of example, those associated with packaging machines are summarized in Table 7.5.

7.3.3.1 Flat Belt Conveyors

Conveyors are responsible for around 30 % of machine-related injuries (HSE 2001b, 2013c). Of these, 90 % involve flat belt conveyors, which include smooth, slatted, mesh, and woven belt types but not bucket, troughed, roller, screw, and rotating table types. The principal British Standards relevant to flat belt conveyors are BS EN 619 (BSI 2002a) and BS EN 620 (BSI 2002b). For details of these and other British standards, consult the BSI Web site (www.bsigroup.com).

About 90 % of conveyor injuries involve well-known hazards such as in-running nips, transmission parts, and trapping points between moving and fixed parts. Also, 90 % of accidents occur during normal, foreseeable operations—production activities, clearing blockages, and cleaning. HSE (2001b) recommends that the following hierarchy of safety measures should be considered for new conveyors; these should also act as a benchmark against which existing conveyors are assessed.

1. *Safety by design*. Hazards associated with in-running nips and other trapping points should be eliminated by good design, e.g., by the use of lift-out rollers and by permanent guarding. The latter, which is welded in place or forms part of the structure, is the best option so long as it prevents the risk of injury and allows for cleaning and the safe clearing of product.
2. *Fixed guarding*. This type of guarding, which can be removed for maintenance and is secured using hand tools by screws, nuts, bolts, etc., can be used when the guard will only have to be removed infrequently. It should either enclose the danger area or prevent access by ensuring a suitable distance to any danger area—see BS EN ISO 13857 (BSI 2008). The disadvantages of fixed guards are that they may not be replaced properly and that access for cleaning may be restricted. Where frequent access to transmission parts is required for adjustment or lubrication, this should be possible without having to remove the guard.
3. *Interlocking guards*. These are guards fitted with coded magnetic interlock switches, which prevent the machine running when they are open. They should be used where guards need to be removed frequently (e.g., daily) for cleaning purposes and clearing blockages, etc. Advantages include ease of access; disadvantages include the need to maintain the interlocks in good working order. Interlocks should be hygienically designed. Their control system and interlocking integrity should comply with the requirements of EN ISO 13849-1 (ISO 2006). Control guards can be used where safety conditions permit (e.g., the operator cannot be trapped in the danger zone, interlocking is to the highest possible reliability, and there is no hazard during the rundown time). These start the machine when they are closed and can be used to reduce downtime.
4. *Tripping devices*. Tripping devices, which may be either mechanically actuated (e.g., trip bars, safety mats) or electrosensitive (e.g., photoelectric) devices, should only be considered where it is not practical to safeguard by other means. These devices should stop the machine before an operator or part of an operator can enter the danger zone. The integrity of mechanical and electrosensitive tripping devices should comply with the requirements of EN ISO 13849-1 (ISO 2006).
5. *Two-hand control*. This is not considered suitable for safeguarding conveyors because it does not offer protection to others who may be in the vicinity.
6. *Other design issues*. The design of all belt conveyors should take the following into consideration:

   - Safe methods of clearing blockages and in-use cleaning (e.g., spray nozzles).
   - Safety at conveyor start-up. It may not be possible for an operator located at the control panel to see all people who may be at risk. In such cases an automatic start-up warning should provided, which would allow an emergency stop control to be operated before the conveyor starts up. Alternatively, mirrors or other viewing aids should be considered.
   - Suitable selection of belt materials. Smooth belts can have different levels of grip, which can increase/reduce the risk of being drawn in. Particular care should be taken where such belts are installed adjacent to each other.
   - The need for trays and drainage to capture drips from belt lubricants.
   - Suitable enclosure/protection for motors, switches, etc., to prevent the ingress of water, cleaning chemicals, etc.
   - Documenting safe methods of work, cleaning methods, etc., in the instruction handbook.

7.3.3.2 Thermoform, Fill, and Seal Packaging Machines

Nearly 50 serious accidents involving thermoform, fill, and seal (TFFS) machines were investigated by the HSE between 1997 and 2001. A third of these were major injury accidents involving amputation and broken bones. About half the injuries were caused by guarding failures at the two main hazard areas, the forming dies and the cutters that separate the continuous packaging into individual packs (HSE 2001c, 2013c).

An analysis of the accidents investigated by the HSE revealed the following principal causes:

- 36 %—guards removed, failed, or inadequate
- 19 %—guarding not provided or fallen into disuse
- 17 %—unsafe systems of work, especially during maintenance

Injury occurred most commonly on manually loaded horizontal, short bed machines, which have insufficient space between the forming and sealing dies to fit tunnel guards that comply with the separation distances specified in BSI (2008).

New TFFS machines should be safeguarded using the techniques described in BS EN 415-3 (BSI 2000b). This standard also covers horizontal and vertical form, fill, and seal machines, bag fill and seal machines, and carton erect/form, fill, and seal/close machines. Safeguarding against the major hazards can be achieved by the following means:

- Tunnel guards over the forming and sealing dies should have reach distances in accord with BSI (2008).
- Where the depth of the opening exceeds 120 mm, as well as the guard extending 850 mm, a pictogram should be attached warning operators of the hazard of reaching into the machine.
- If it is not possible to achieve the required reach distances for the guards, the following options should be considered: trip guard, trip guard with deterring device, light-sensitive trip device, linked automatic guarding, and automatic guard.

7.3.3.3 Preformed Rigid Container Packaging Machines

This wide-ranging category of packaging machines accounted for 45 serious accidents investigated by the HSE between 1997 and 2001. The principal hazards are mechanical in nature, moving parts that give rise to shearing, puncture, cutting, and entanglement hazards. An additional hazard is the ejection of containers or container parts, particularly where pressurized filling is carried out.

The following hierarchy of safeguarding measures is recommended in HSE (2001d):

- Avoid mechanical hazards by design.
- Fixed guards.
- Interlocked guards.
- Electrosensitive protective equipment (ESPE).
- Adjustable guards.
- Protective structures.

Safety distances for guards are given in BS EN ISO 13857 (BSI 2008).

On high-speed rotary machines and packing or unpacking transfer mechanisms, the operation of an emergency stop or a power failure can cause the loss of operational stability or the dropping and/or breakage of a container. Machines should be designed to minimize the hazards resulting from such eventualities. Any cutting tools should be capable of being removed and replaced safely.

HSE (2001d, 2013c) list a large number of machine-specific hazards and safeguards that were originally set out in BS EN 415-2 (BSI 2000a). The reader is referred to either of these publications for further details.

7.3.3.4 Palletizers and Depalletizers

Most palletizer/depalletizer accidents happen when operators or maintenance personnel enter the machine and become trapped between fixed and moving parts such as transfer heads, sweepers, and pushers. Entry into the machine is necessary for adjustment, clearing of blockages, cleaning, and maintenance. Additional hazards also arise from falling loads, sudden movement of jammed product or pallets when they are freed, and by movement due to the failure to dump stored energy in pneumatic and hydraulic systems. The HSE investigated 30 serious and fatal accidents involving palletizers and depalletizers between 1997 and 2001.

The safeguarding requirements for new plant described in HSE (2001e, 2013c) are based on those set out in BS EN 415-4 (BSI 1998). Entry into the machine should be via a dedicated route other than the pallet load entry/exit openings. Doors provided for this purpose should be fitted with interlocking devices with guard locking, and openings should have suitable electrosensitive protective equipment (EPSE) acting as a trip. In practice, a perimeter fence with interlocked personnel doors and photoelectric safety systems at the pallet entry and exit points should be employed. Inside the machine, all movable parts that are accessible should be protected by fixed guards.

Following the entry of a worker into the palletizer or depalletizer, it should only be possible to restart the machine by an intentional action at a control device located outside the danger zone. Trapped key interlocking devices or presence-seeking devices should be provided in order to prevent the machine being restarted by a third party while a worker is still inside it. It should also be possible for an operator located at the main control panel to ensure that there are no people in a position where they may be put at risk.

The entry of an operator through the entry or exit points for pallet loads, unit loads, or empty pallets should be prevented by at least one of the following methods:

- Electrosensitive protection equipment. These systems can discriminate between a person and a load on the basis of, e.g., length. Alternatively, they can be designed to detect the direction of motion and the size of an object. If these do not match those of a pallet load, a stop command is initiated.
- Interlocked moveable guards. These are unlocked when a pallet is ready to be discharged. The pallet then pushes the guards open. Once the pallet has passed through the resulting opening, the guards then close automatically with, for example, the aid of springs. The next cycle can only start when the lock on the guards is closed.
- Fixed guarding. This should be at least long enough to accommodate two loaded pallets. The first pallet can only be removed when the second pallet, which acts as a barrier, is in position. This method should only be used in low-risk applications on palletizer exit points as no protection is provided at start-up.

7.3.4 Slips and Trips

There is a high rate of occurrence of accidents caused by slips and trips in the food industry principally because of wet or greasy floors. For example, it is the principal cause of major accidents in bakeries (HSE 2011e). On average, slips and trips cause 40 % of all reported major injuries at work (HSE 2011f) and can give rise to other types of serious accident, e.g. falls from height (HSE 2012). HSE (1996) provides provides basic guidance on how to minimize the occurrence of slips and trips in the food processing industry. It also sets out the legal requirements for UK employers.

Slips account for the majority of the total slips and trips injuries. In most cases they happen because the floor is wet. Table 7.6 summarizes causative factors and practical measures for controlling the risk of slips; equivalent information for trips is given in Table 7.7. In these tables,

Table 7.6 Causative factors and practical measures for controlling the risk of slips

Causative factor	Practical control measure
Environmental factors	
(a) Contamination of the floor (e.g., from spillages, wet cleaning methods, etc.)	1. *Eliminate contamination in the first place* 2. Prevent contamination becoming deposited on walking surfaces 3. Limit the effect of contamination
(b) Inherent slip resistance of the floor not maintained adequately (e.g., from incorrect or inadequate cleaning or maintenance, or wear)	4. Maximize the surface roughness and slip resistance of the existing floor surface (e.g., follow an effective cleaning regime as indicated by the floor supplier to remove even thin layers of contamination and cleaning agent residue)
(c) The slip resistance of the floor is too low	5. Maximize the surface roughness of the existing floor (e.g., by sticking on anti-slip strips). *Lay a more slip-resistant floor with a higher surface roughness*
(d) Steps and slopes: do they cause sudden changes in step or not offer adequate foot hold and/or hand hold?	6. *Ensure that steps and slopes give adequate foot and hand hold and have no sudden changes in level*
(e) Adverse conditions hiding the floor conditions and distracting attention	7. *Ensure that the prevailing conditions allow good visibility of and concentration on floor conditions (*e.g., *provide adequate lighting and avoid distracting environmental factors)*
Organizational factors	
(f) The nature of the task (the need to lift or carry loads, to turn, move quickly, or to take long strides, distractions, having no hands free to hold on or to break a fall)	8. *Analyze the tasks to ensure that no more than careful walking is required in any slip area (*e.g., *tasks should be mechanized to avoid the need for lifting, carrying, pulling,* etc.*, on a slippery floor; moved to a safer area; or slowed down)*
(g) Placing vulnerable individuals (e.g., untrained, having poor health, agility or eyesight, or fatigued) at risk	9. Allocate tasks in slip-risk areas only to those competent to follow slip precautions
(h) Having insufficient supervision	10. Supervise to monitor physical controls and to ensure that safe practices are followed
(i) Having a safety culture that is not supportive	11. Establish a positive attitude to enable slip risks to be controlled
Personal protective equipment: shoe factors	
(j) Shoes offer insufficient slip resistance in combination with the floor surface	12. Select suitable shoes for the floor, environment, and individual (microcellular urethane and rubber soles are the least slippery on level wet floors). Ensure that the shoes are well maintained, free from contamination, and replaced before they have worn smooth
Individual factors	
(k) Unsafe actions of staff (e.g., lack of awareness of the risk, knowledge of how slips occur, information and training, or distraction or carelessness)	13. Train, inform, and supervise employees (e.g., on the risk, control arrangements, and employee roles)

Adapted from Table 1 of Food Information Sheet No. 06 (1998) published by the Health and Safety Executive. This is no longer available online

the practical control measures indicated in italics should be considered at the design stage. Broadly speaking, these fall into five categories:

1. If possible, eliminate contamination in the first place. This can be achieved by employing enclosed equipment and transfer systems or, if necessary, bund walls around equipment. Effective ventilation should be employed to extract fumes and steam.

Table 7.7 Causative factors and practical measures for controlling the risk of trips

Causative factor	Practical control measure
Environmental factors	
(a) Uneven surfaces (e.g., gulleys, holes, steps)	1. Eliminate holes, slopes, or uneven surfaces, which could cause trips. Inspect and maintain the floors; highlight any changes in level and make slopes gradual and steps clearly visible; avoid open gulleys and channels
(b) Obstructions (e.g., accumulation of work in progress, waste)	2. Good housekeeping: *(a) eliminate materials likely to obstruct and cause trips* (e.g., *analyze work flows and design process so that waste and product does not accumulate)*, (b) prevent material obstructing (e.g., provide sufficient, correctly sited receptacles for work in progress; ensure that walkways, working areas, and receptacle locations are marked out and kept free from obstruction)
(c) Adverse environment (e.g., inadequate illumination to see the floor properly or glare)	3. *Provide suitable lighting to permit obstructions to be seen*
Organizational factors	
(d) The nature of the task creates obstructions	4. *Analyze the tasks and process flows to see if the work can be handled to eliminate or minimize these obstructions*
(e) Safety culture is not supportive	5. Establish a positive attitude so that trips can be prevented
Individual factors	
(f) Safe practices are not followed	6. Train, inform, and supervise employees

Adapted from Table 2 of Food Information Sheet No. 06 (1998) published by the Health and Safety Executive. This is no longer available online

Table 7.8 Typical minimum roughness levels consistent with a low slip potential for different contaminants (After HSE 2007)

Minimum roughness, μm	Contaminant
20	Clean water, coffee, soft drinks
45	Soap solution, milk
60	Cooking stock
70	Motor oil, olive oil
>70	Gear oil, margarine

2. Ensure that the slip resistance of the floor is adequate for the job. HSE (2007) provides the latest guidance on floor specifications and the measurement techniques. Table 7.8, extracted from this publication, summarizes the minimum values of peak-to-valley roughness required to give satisfactory slip resistance under different conditions.
3. Where changes of level are required, ensure that steps and slopes are properly specified. They should provide adequate foot and hand hold and gradients should be gentle.
4. Sufficient lighting should be provided to make any contamination of the floor clearly visible. Particular attention should be paid to steps and slopes.
5. Work flows should be analyzed. Adequate storage areas (not walkways) for product, materials, and work in progress should be provided. Allow for, e.g., lifting gear and mechanical transportation in slippery areas so that mechanical handling can be avoided.

7.3.5 *Handling and Lifting*

Manual handling is the single largest cause of acute physical injury (30–34 % of reported cases) and occupational ill-health (around 40 % of reported cases) in the food and drink industry. Ill-health cases include work-related upper limb disorders (WRULDs), also known as repetitive strain injury (RSI), and back and lower-limb (musculoskeletal) disorders. The Manual Handling Operations (Regulations 1992), which came into effect on 1 June 1993, set out the principal legal requirements relating to manual handling activities such as lifting, pulling down, pushing, pulling, carrying, or moving by hand or bodily force. The Regulations require that manual handling be avoided as far as is practical by, for example, mechanization. Where this is not possible, a risk assessment (see Sect. 7.5) should be carried out to reduce the risk by, for example, altering the layout. These possibilities should naturally be considered at the design stage.

Discussions between industry stakeholders and the HSE led to the identification of the priorities listed below (HSE 2013e). As is normally the case, possible remedies involve factory design considerations as well as operational procedures.

1. *Stacking and destacking*. Stacking and destacking sacks, boxes, and crates are a leading cause of manual handling and musculoskeletal injuries. Where possible, full mechanical handling of containers should be employed using, for example, vacuum bag-lifting devices, conveyors, and computerized vacuum lift-assisted palletizers. Such methods, which should be considered when large numbers of containers and/or heavy containers need to be handled, should be included in the factory design. Alternatively, the use of mechanical devices that assist manual handling may be appropriate. Failing this, the weight of unit loads should be reduced to ideally 25 kg or less.
2. *Pushing wheeled racks*. Wheeled racks (or trolleys) are used widely in the food and drink industry to transport up to 400 kg or more loads of product around the factory or into storage. They are typically half-pallet size and comprise a tall metal frame with up to 20 shelves, which are often removable. The racks usually run on four swivelling running castors. Musculoskeletal injuries can be reduced by proper specification of the walkways along which the racks will be moved, including minimizing the number and gradients of slopes and the selection of racks of an appropriate design. The castors, in particular, should permit ease of movement. They should be of relatively large diameter (e.g., 125 mm), located close to the corners of the rack to ensure stability, and of suitable construction. HSE (2013d) gives further details of these and operational safety measures.
3. *Cutting, boning, jointing, trussing, and evisceration* (e.g., meat and poultry). These operations are essentially manual in nature. There are few if any implications as far as the factory design is concerned apart from the provision of suitable equipment and space.
4. *Packing* (e.g., cheese, confectionery, biscuits). The possibility of mechanical packaging should be investigated at the factory design stage. Other considerations of an operational nature include job rotation and rate of working.
5. *Handling drinks containers*. Consider the use of mechanical aids where practicable, combined with training in correct handling procedures.

HSE (2013e) presents in some detail a number of solutions to minimize manual handling problems in food factories.

Manual handling problems can be exacerbated by cold workroom temperatures. Health and safety law in the UK requires that a "reasonable" workroom temperature of at least 16 °C, or at least 13 °C if the work involves serious physical effort, should be met. HSE (2011g) discusses alternative arrangements where this is not practical. Clearly, possible options should be considered at the factory design stage, particularly when there is an apparent conflict with a legal requirement to meet proscribed hygiene standards by maintaining a lower food-product temperature.

7.3.6 Being Struck by Objects

Being injured by a moving object (whether falling or otherwise) accounts for over 10 % of major injuries reported to the HSE in the food and drink industry (HSE 2011h). Most injuries fall into the three categories listed below. Precautionary measures are also described.

1. *Falling objects*
    - Ensure that items stored above ground level are stable. Store heavier items on or near the ground.
    - Consider carefully the methods employed to prevent articles falling during stacking, handling, and moving.
    - Make sure that tall free-standing objects (e.g., gas cylinders) or objects leaning against walls are either stable or secured.
2. *Hand tools*
    - Hand knives, which cause the greatest number of injuries, should be safely sheathed and stored when not in use.
    - When hand knives are in regular use, knife-resistant protective clothing, as identified by a risk analysis, should be worn.
    - Maintain hand tools in good condition to prevent the need for excessive force when using them.
3. *Moving objects*
    - Pedestrian operated pallet trucks, racks, trolleys, etc., should operate on designated routes free from other workers, if possible. The operator should have good visibility.
    - Other specific hazards (e.g., rolling barrels, hoist hooks, items ejected from machines) should be identified by means of a risk analysis and precautionary measures taken to avoid accidents.

    Clearly, the above two items are best considered at the factory design stage.

7.3.7 Dust Explosions

Fortunately, dust explosions are not frequent in the food and drink industry. However, when they do occur, they can give rise to major accidents involving multiple fatalities, severe injuries, and extensive structural damage. HSE (2011i) describes the precautions that should be taken in food plants handling potentially explosible dusts. This publication also cites a number of additional references that provide further valuable advice. Given the nature of this particular hazard, it is essential that safety measures should be considered at the planning stage and incorporated into the factory design.

HSE (2011i) lists the following explosible dusts encountered in the food industry: flour, custard powder, instant coffee, sugar, potato powder, and soup powder. Common processes generating explosible dust include flour and provender milling, sugar grinding, spray drying of milk, and conveying of whole grains and finely divided materials.

A dust cloud of flammable material will explode when:

- The concentration of dust in the air falls within the explosive limits
- Sufficient oxygen is present
- A source of ignition having the required energy is present

Prevention of an explosion can be based on the avoidance of at least one of these conditions. However, this can never be guaranteed. One or more of the following additional precautionary measures should therefore be taken: inerting, prevention of secondary explosions, explosion relief, explosion suppression, explosion containment, and building design. HSE (2011i) lists the following advice:

1. Locate plant in the open air or in a lightweight building so that the roof or wall cladding panels can act as explosion relief. On older brick/stone-built premises, provide the maximum area of explosion relief that is reasonably practicable. Aim for a minimum of 1 m^2 per 24 m^3 of building volume.
2. Enclose plant and equipment to prevent escape and accumulation of dust in the building.
3. Maintain scrupulous cleanliness including, normally, a centralized vacuum cleaning system.
4. Maintain a slight negative pressure on storage vessels such as bins and silos by the use of extraction systems.
5. Provide adequate arrangements for separating powder from its transporting air when pneumatic conveying systems are used.
6. Fit silos and bins with explosion relief.
7. Equip dust-collecting silos with explosion relief and a rotary valve at the base to act as an explosion choke. If the explosion relief is located above the vortex finder, it is essential that the strength of the vortex finder ("thimble") is adequate to withstand an explosion within the cyclone without collapsing.
8. Totally enclose dust-collecting filter units and fit with explosion relief.
9. Equip bucket elevators (unless wooden) with explosion relief at the head of the elevator. Fit each leg of the elevator with explosion relief panels equal in area to the cross-sectional area of the leg. These panels should be located every 6 m (maximum).
10. Preferably, fit bucket elevators with underspeed switches and alignment motors.
11. Exclude obvious ignition sources. Use electrical equipment dust protected to IP5X or IP6X, depending on dust levels. Surface temperatures should be controlled to a maximum of 200 °C (lower for milk powder, some fish meals, and other products containing unsaturated oils). Prohibit the use of inspection lamps with flexible cables. To check levels in bins, use explosion-proof battery hand lamps secured against accidental dropping or tripods with fixed lamps placed over inspection hatches. Use an effective permit-to-work system to control hot work, welding, etc.
12. To prevent the onward transmission of burning material, equip all explosion reliefs with index switches to close down the plant in the event that they are activated.

7.4 Occupational Health

"A Recipe for Safety" (HSE 2005) makes the following statement in relation to occupational health:

"Every year, in all industries, 1.5 million workers suffer from ill health caused or made worse by work. In the food and drink industries, an estimated 29,000 workers (4.8 % of the workforce) suffered from ill health caused or made worse by work during 2001/02, according to the Self-reported Work-related Illness (SWI) Survey for those years. This compares with 2.2 % of workers receiving an injury reported to HSE under RIDDOR during the same year.

From these data, the risk of a worker suffering occupational ill health at work in the food and drink industries is more than twice that of sustaining an injury. This is reflected in civil claims; more claims now result from occupational ill-health issues than from safety issues—reversing the trend in earlier years.

HSE (2005) cites the following priority diseases: musculoskeletal disorders (MSDs), work-related stress, occupational asthma, occupational dermatitis, rhinitis, and noise-induced hearing loss.

7.4.1 Musculoskeletal Disorders (MSDs)

This topic was covered in Sect. 7.3.5. From an occupational health point of view, musculoskeletal disorders cover a variety of strain, sprain, and overuse problems affecting the body's muscles and joints. It includes everything from backache and slipped discs to work-related upper limb disorders (WRULDs), tenosynovitis, repetitive strain injury (RSI), pain, numbness, swelling, and tingling in the hands and wrists.

Musculoskeletal disorders can be caused by lifting heavy or awkward loads or by repeated awkward movements on, for example, packing lines and poultry lines. These actions can result in back injuries (35 % of reported cases of occupational ill-health) and upper limb disorders (23 % of reported cases) and permanent disability if no action is taken or not taken in time.

7.4.2 Work-Related Stress

No data are cited in HSE (2005) relating to the prevalence or causes of work-related stress in the food and drink manufacturing industries. However, this condition is often claimed to be a cause of medically diagnosed mental ill-health (e.g., depression), which accounted for 29 % of cases of occupational ill-health reported by specialist doctors under THOR (The Health Occupation Reporting Network) and FIMA (Food Industry Medical Association) during 2001–2003.

The following causes of work-related stress are listed in HSE (2005):

- Poor work organization
- Pressure experienced by an individual in excess of his/her ability to cope with it
- Excessive work demands, lack of control over work, etc.

For more information on stress in the workplace, see HSE (2011j).

7.4.3 Occupational Asthma

According to THOR, the prevalence of occupational asthma is around 105 cases per 100,000 workers (HSE 2005). This represents about 6 % of work-related ill-health cases. Occupational asthma is a debilitating and potentially life-threatening disease, the symptoms of which include wheezing, chest tightness, or breathlessness. It is caused by (rather than being made worse by) inhaling substances, which produce a hypersensitive state in the lungs. Not everyone who becomes sensitized falls victim to the full effects of the disease. However, once the lungs have become hypersensitive, further exposure to the substance, even at low levels, can bring on an attack.

In the food industry, asthma may be brought about by exposure to dust from grain, flour, spices, fish protein, wood, and certain process additives associated with these materials (HSE 2011k). Consequently, workers involved in milling, malting, baking, fish processing, and coopering are at particular risk. Naturally, there may well be other substances used in the factory that could give rise to asthma as well as other health hazards that need to be taken into consideration.

In the UK, exposure to harmful substances, such as those that could give rise to asthma, is regulated by the Control of Substances Hazardous to Health Regulations 2002 (COSHH). These take into consideration the nature of the material, its physical state, and the process to which it is subject. For an overview of this legislation, consult “Working with substances hazardous to health. What you need to know about COSHH” (COSHH 2011).

In order to ensure that employees’ health is not put at risk through contact with harmful substances, COSHH sets out eight basic measures that employers, and sometimes employees, must take. These are as follows:

1. Assess the risks to health arising from hazardous substances used in or created in the workplace.
2. Decide what precautions are needed to prevent the workforce from being exposed to risk and to comply with COSHH.
3. Prevent or adequately control exposure.
4. Ensure that control measures are used and maintained properly and that safety procedures are followed.
5. If necessary, monitor the exposure of employees to hazardous substances.
6. Carry out appropriate health surveillance where your assessment shows this to be necessary or where specifically required by COSHH.
7. Prepare plans and procedures to deal with accidents, incidents, and emergencies involving hazardous substances, where necessary.
8. Ensure employees are properly informed, trained, and supervised.

In order to determine the precautions necessary to control exposure to hazardous substances, the reader may wish to consult the interactive Web site www.COSHH-essentials.org.uk. Permissible exposure limits are given in HSE (2011l).

Control of hazardous dust levels in the factory that could give rise to occupational lung (and other) diseases should be considered at the design stage after a risk assessment has been carried out. In particular, the installation of adequate local exhaust ventilation to meet COSHH requirements is appropriate and necessary.

The REACH (*R*egistration, *E*valuation, *A*uthorization, and restriction of *CH*emical substances) legislation, which is complementary to COSHH, came into force in the European Union on 1 June 2007. For further details, see EC (2007). Two of the principles underlying this legislation are to provide a high level of protection of human health and the environment from the use of chemicals and to make the people who place chemicals on the market (manufacturers and importers) responsible for understanding and managing the risks associated with their use (HSE 2011m).

7.4.4 Occupational Dermatitis

Occupational dermatitis is caused by the skin coming into contact with substances at work. Symptoms of this condition can be redness, itching, scaling, and blistering of the skin. If dermatitis is spotted early enough and adequate precautions are taken, most people will make a full recovery. However, some people never recover because of sensitization.

Many cases of dermatitis are caused by contact with food: sugar, flour/dough, citrus fruits and their peel, other fruits, vegetables, spices, herbs and seasonings (e.g., horseradish, mustard, garlic), fish and seafood, and meat and poultry (HSE 2011n). Other substances giving rise to the condition include nickel, as for example in coins, rubber (including rubber gloves), and various chemicals and cleaners. Prevention of dermatitis is relatively simple:

1. Find out if there is a problem. (Do workers come into contact with the above substances? Do sickness reports indicate skin problems? Investigate workers’ complaints. Consult safety representatives and employees.)
2. Determine the cause of the problem.

3. Propose a cure. Possibilities include elimination of the offending substance (where possible), protection by, for example, wearing suitable gloves, job rotation, or redeployment to alternative duties.
4. Monitor the results.
5. Train and inform workers.

Thus, prevention of dermatitis is primarily an operational problem. It has few implications at the factory design stage.

7.4.5 Rhinitis

Rhinitis (runny or stuffy nose) accounts for around 2 % of reported cases of occupational ill-health in the food industry (38 cases per 100,000 workers). It results from exposure to irritant dusts, such as grain, flour, spices, and seasonings (HSE 2011k), that cause inflammation of the nasal mucous membranes. These dusts can also cause conjunctivitis (watery or prickly eyes) and other irritant effects.

7.4.6 Noise-Induced Hearing Loss

Being exposed to noise at work can cause irreversible hearing damage, which can be difficult to detect as the effects build up gradually over time. Consequently, in the UK, the Noise at Work Regulations 2005 (Regulations 2005) require employers to have a competent person assess noise levels to which workers are exposed. If the noise level exceeds 85 dB(A), the so-called First Action Level, employers are required to inform their workers about the risks to their hearing. They are also required to provide hearing protectors to employees who request them; in such cases, they should provide appropriate instruction and training. If the noise level exceeds 90 dB(A), the Second Action Level, employers are required to do all that is reasonably practicable to reduce this to below 90 dB (A) by any means other than providing hearing protectors. If this is not possible, such zones should be marked with clearly visible signs to restrict entry. Employees working in these zones are required to make full and proper use of hearing protectors. For further guidance on the application of these regulations, see HSE (2011o).

Table 7.9 (HSE 2000) lists typical noise levels recorded in food and drink factories. As may be seen, the Action Levels are exceeded in many areas in the factory in which machinery is operated. HSE (2013g) proposes a hierarchy of control measures to reduce noise levels to below 90 dB(A). Protection is best achieved by controlling noise at source; wearing hearing protection should be regarded as a last resort. The hierarchy is as follows:

1. When purchasing new plant or equipment, take noise levels into account. Obtain emission data from the manufacturer or supplier to aid your decision. The data should specify noise levels at the positions occupied by the operators.
2. Install noisy plant and machinery in areas where there are no or few workers (e.g., in an outbuilding or dedicated room).
3. Where noisy plant and machinery has to remain in the working area, enclose it within a sound-insulating enclosure if possible.
4. Where enclosure is not practicable, reduce noise by suitable engineering means. Examples include the following: lining guards/panels with noise-dampening material, providing acoustic screens, lining the inside of hoppers with impact-deadening material, fitting anti-vibration

Table 7.9 Noise level in the food and drinks industries (After HSE 2002)

Sector	Operation	dB(A)	Sector	Operation	dB(A)
Drinks	Bottling halls	85–95	Bakery	Dough-mixing room	85
	Bottle filling/labelling	85–95		Baking plant	85
	De-crating/washing	85–96		De-panning	90
	Casking/kegging	85–100		Bread slicing	85–90
	Cooperage machines	>95		Fruit washing	92
Meat	Animals in lairage	80–110	Dairy	Production areas	85–95
	Powered saws	<100		Homogenizers	90–95
	Blast freezers/chillers	85–107		Bottling lines	90–95
	Bowl choppers	>90		Blast chillers	87–95
	Packing machinery	85–95		Pneumatics	85–95
Milling	Mill areas	85–95	Confectionery	Hopper feed	95
	Hammer mills	95–100		Mold shakers	90–95
	Grinders	85–95		Wrap/bagging	85–95
	Seed graders	90		High boiling	85
	Bagging lines	85–90			

machine mountings, fitting silencers to exhaust systems, and undertaking effective maintenance to eliminate rattles and prevent noise from wear.

5. Where the 90 dB(A) threshold is still exceeded, ensure that workers wear adequate hearing protection within the designated and clearly marked zones.
6. Reduce the exposure of individual workers by job rotation or providing a noise refuge.

HSE (2002, 2013g) provide examples of solutions to the following noise problems frequently encountered in the industry: glass bottling, product impact on hoppers, wrapping, cutting wrap, bagging (e.g., sweets), bowl choppers (meat), pneumatic noise and compressed air, milling operations, saws/cutting machinery, blast chillers/freezers, manually pushed wheeled trolleys/racks, and packaging machinery.

Clearly, there is ample opportunity to incorporate effective noise control measures at the factory design stage. Where possible, plant and equipment with relatively low noise-emission levels should be purchased. This is obviously the most effective way of protecting workers' hearing and complying with the law. Alternatively, locate noisy equipment in specially designed areas in which few employees work. This is a less satisfactory solution, which could in addition prove to be a more expensive option and limit production flexibility and future expansion.

7.5 Risk Assessment

7.5.1 *Existing Factories*

In Sects. 7.3 and 7.4, safety and health hazards of particular concern to the food and drink industry were discussed. In any given factory, risks associated with these and other more general hazards (electrical, fire, use of display screens, personal protective equipment, etc.) need to be evaluated. This is done through a risk assessment. HSE (2011p) lists the five steps that constitute such an assessment:

1. Look for the hazards. In an existing factory, periodic, properly conducted safety inspections should suffice to identify the risks. These should be carried out by safety professionals or experienced staff and will undoubtedly concentrate primarily on significant hazards.

2. Decide who may be harmed and how. A safety assessment should consider everybody who is likely to come into contact with the hazard. This includes operators, maintenance workers, contractors, other technical and managerial staff, and visitors. Young workers, new and expectant mothers, etc., may be at particular risk.
3. Evaluate the risks and decide whether the existing precautions are adequate or whether more should be done. Consider the following questions:

   If the answer to each is "yes," then the precautions taken are probably adequate. However, even after all the above precautions have been taken, it is likely that some residual risks will remain. Are these acceptable (i.e., "low")? If not, more needs to be done.

   - Have all basic legal requirements (e.g., guarding to prevent access to moving machinery) been met?
   - Are all generally accepted industry standards in place?
   - Has everything reasonably practicable been done to ensure that the workplace is safe?

4. Record the findings. It is always advisable to keep a written record of the results of health and safety assessments, even when not required to do so by law. This should include both positive and negative aspects and the results should be communicated to the workforce. The record should show that a proper check was made, that all those who might be affected were consulted, that the obvious significant hazards were dealt with, that the precautions taken were reasonable, and that the remaining risk was low.
5. Review the assessment and revise if necessary. When new equipment, materials, or processes are introduced into the factory, a further assessment should be carried out to assess and record significant changes.

In practice, health and safety legislation is included in a number of Acts, each of which has a somewhat different emphasis. HSE (2011q) provides additional guidance on how to satisfy these multiple requirements in the UK.

7.5.2 Factories at the Design Stage

Many potential hazards can be avoided by carrying out a safety and health assessment as part of the factory design before any contracts for building work or equipment purchase have been placed. At this stage, any changes introduced will involve a relatively small expenditure. The process involves perusal of architects' plans, flow sheets, utility diagrams, equipment lists and specifications, layout drawings, proposed operating and maintenance procedures, etc. This exercise is best undertaken by a team, which includes a range of relevant disciplines—e.g., civil, mechanical, electrical, and process engineers, a medical specialist, a food technologist, and a microbiologist, as well as a safety specialist. In this way, a variety of skills will be brought to bear on the subject. This approach is widely used in the chemical industry, where hazard and operability (HAZOP) studies are routinely used to minimize risk. The technique involves a careful examination of each segment of the process (equipment, pipelines, conveyors, instruments, etc.). All possible deviations from normal operating conditions are identified and their effect on the safety of the plant evaluated. Any hazard thus identified is eliminated by modifying the design. This process continues until the remaining residual risk is acceptably low. A summary of this technique is given in Peters et al. (2003).

7.6 Managing Occupational Safety and Health

There are many similarities between the management of occupational health and safety, quality, and environmental protection programs. An international standard, ISO 9000, has been developed for quality management and is widely accepted worldwide. It provides organizations with a process for producing quality products through a systems approach that involves all phases of production. The more recent ISO 14000, discussed more fully in Chap. 8, provides a similar framework for environmental protection.

One major difference between ISO 9000 and ISO 14000 is that the latter requires the implementation of an ongoing process of evaluation and improvement. This is clearly a desirable feature of any occupational health and safety management (OHSM) system. It has therefore been proposed that a comparable international standard be drawn up for this purpose. However, for a variety of reasons, this proposition was not followed up due to a lack of support. However, the OHSM system model developed by the American Industrial Hygiene Association (AIHA) closely follows that of ISO. Thus it can be introduced at the design stage and progressively refined during the operational life of the factory.

The AIHA Guidance Document contains both specifications and useful interpretations. The first three sections detail the scope, references, and definitions. The introduction to Sect. 4 of the AIHA publication describes the principles upon which an OHSM system should be based. The remainder of the section addresses the following aspects of the system:

1. Management Responsibility for OHS
2. OHS Management Systems
3. OHS Compliance and Conformance Review
4. OHS Design Control
5. OHS Document and Data Control
6. Purchasing
7. OHS Communication Systems
8. OHS Hazard Identification and Traceability
9. Process Control for OHS
10. OHS Inspection and Evaluation
11. Control of OHS Inspection, Measuring, and Test Equipment
12. OHS Inspection and Evaluation Status
13. Control of Nonconforming Process or Device
14. OHS Corrective and Preventative Action
15. Handling, Storage, and Packaging of Hazardous Materials
16. Control of OHS Records
17. Internal OHS Management System Audits
18. OHS Training
19. Operations and Maintenance Service
20. Statistical Techniques

Further details of these aspects are described in Ritchie and Hayes (1998). An OHSM system should be specific to each organization and be implemented in the context of organizational policies, statutory, and regulatory requirements, recommended guidelines, and labor agreements. It is clear from the above list of topics that considerable thought and detail is required in order to draft and implement a comprehensive and effective OHSM system. It requires highly competent staff with appropriate training, experience, and professional judgement.

Finally, as noted above, the system should incorporate continuous improvement as one of its underlying principles. This process involves the adoption of improvements in technology and control methods. It also requires the adoption of strategies to promote safe behavior in the workplace; these have been discussed by Fleming and Lardner (2002).

7.7 Conclusion

This chapter presents an overview of some of the more important issues affecting the safety and health of employees, contractors, and visitors in a typical food factory. Clearly, it has not been possible to cover all eventualities as each manufacturing facility will present different challenges. For example, accidents resulting from entry into silos (HSE 2011r), which used to be a major problem in the past, has only received a brief mention. Although it is ultimately the responsibility of management to put in place all the necessary measures to ensure the well-being of every person in the factory, each individual needs to play his or her part in contributing to a safe and healthy working environment.

References

BLS (2011a) “Injuries, illnesses, and fatalities in food manufacturing, 2008", Nivedita L. Bhushan, Bureau of Labor Statistics, US Department of Labor, posted 21 Jan 2011, http://www.bls.gov/opub/cwc/sh20110118ar01p1.htm.

BLS (2011b) “National census of fatal occupational injuries in 2010”, Bureau of Labor Statistics, US Department of Labor, News Release, 25 Aug 2011, http://www.bls.gov/news.release/pdf/cfoi.pdf.

BSI (1998) “Safety of packaging machines – Part 4: Palletisers and depalletisers”, BS EN 415–4, British Standards Institute, London.

BSI (2000a) “Safety of packaging machines – Part 2: Pre-formed rigid container packaging machines”. BS EN 415–2, British Standards Institute, London.

BSI (2000b) “Safety of packaging machines – Part 3: Form, fill and seal machines”, BS EN 415–3, British Standards Institute, London.

BSI (2002a) “Continuous handling equipment and systems. Safety and EMC requirements for equipment for mechanical handling of unit loads”, BS EN 619, British Standards Institute, London.

BSI (2002b) “Continuous handling equipment and systems. Safety and EMC requirements for fixed belt conveyors for bulk materials”, BS EN 620, British Standards Institute, London.

BSI (2008) “Safety of machinery. Safety distances to prevent hazard zones being reached by upper and lower limbs”, BS EN ISO 13857, British Standards Institute, London.

COSHH (2011) “Working with substances hazardous to health. What you need to know about COSHH”, Health and Safety Executive, INDG136(rev4), July. Available online at www.hse.gov.uk/pubns/indg136.pdf.

DETR/HSC (2000) “Revitalising health and safety”, Department of the Environment, “Transport and the Regions”, London, June.

EC (2007) “Registration, Evaluation, Authorization and restriction of CHemical substances (REACH)”, European Union Regulation on chemicals and their safe use”, http://ec.europa.eu/environment/chemicals/reach/reach_intro.htm.

Fleming, M. and Lardner, R. (2002) “Strategies to promote safe behaviour as part of a health and safety management system”, HSE Books, Sudbury, Sussex, England, April 2002, ISBN 0-7176-2352-1. Available online at www.hse.gov.uk/research/crr_pdf/2002/crr02430.pdf.

Fraser, I. (2010) (ed.) Guide to the application of the Machinery Directive 2006/42/EC, 2nd edit., European Commission - Enterprise and Industry, June, 404 pp. Available online at http://ec.europa.eu/enterprise/sectors/mechanical/files/machinery/guide-appl-2006-42-ec-2nd-201006_en.pdf.

HSE (1996) “Slips and trips. Guidance for the food industry”, HSG156, HSE Books, Sudbury, Sussex, England, ISBN 0-7176-0832-8.

HSE (1999) “Workplace transport safety in food and drink premises”, Food Information Sheet No. 21, Health and Safety Executive, May.

HSE (2000) “Securing health together”, HSE Books, Health and Safety Executive, London, 37pp., http://books.hse.gov.uk/hse/public/saleproduct.jsf?catalogueCode=MISC225.

HSE (2001a) “Preventing falls from height in the food and drink industries”, Food Information Sheet No. 30, Health and Safety Executive, July.
HSE (2001b) “Safeguarding flat belt conveyors in the food and drink industries”, Food Information Sheet No. 25, Health and Safety Executive, April.
HSE (2001c) “Packaging machinery: safeguarding thermoform, fill and seal machines”, Food Information Sheet No. 26, Health and Safety Executive, September
HSE (2001d) “Packaging machinery: safeguarding pre-formed rigid container packaging machines”, Food Information Sheet No. 28, Health and Safety Executive, September.
HSE (2001e) “Packaging machinery: safeguarding palletisers and depalletisers”, Food Information Sheet No. 27, Health and Safety Executive, September.
HSE (2002) “Reducing noise exposure in the food and drink industries”, Food Information Sheet No. 32, Health and Safety Executive, March.
HSE (2005) “A recipe for safety”, HSE Books, Sudbury, Sussex, England, ISBN 987 0 7167 6115 2, 30 pp. Available online at www.hse.gov.uk/pubns/priced/hsg252.pdf.
HSE (2007) “Assessing the slip resistance of flooring”, Health and Safety Executive, March. Available online at www.hse.gov.uk/pubns/web/slips01.pdf.
HSE (2011a) “The ‘Recipe for Safety’ Initiative”, Health and Safety Executive, 29 September, www.hse.gov.uk/food/recipeforsafety.htm.
HSE (2011b) “Success of the Recipe for Safety Initiative”, Health and Safety Executive, 29 September, www.hse.gov.uk/food/recipesuccess.htm.
HSE (2011c) “Health and Safety Executive Annual Statistics Report 2010/11”, undated, www.hse.gov.uk/statistics/overall/hssh1011.pdf.
HSE (2011d) “Buying new machinery – A short guide to the law and your responsibilities when buying new machinery for use at work”, Health and Safety Executive, September. Available online at www.hse.gov.uk/pubns/indg271.pdf.
HSE (2011e) “A Baker’s dozen. Thirteen essentials for health and safety in bakeries”, Health and Safety Executive, July. Available online at www.hse.gov.uk/pubns/priced/hsg233.pdf.
HSE (2011f) “Preventing slips and trips at work”, INDG225(rev1), Health and Safety Executive, September 2011. Available online at www.hse.gov.uk/pubns/indg225.pdf.
HSE (2011g) “Chilled and frozen products. Workroom temperatures in places where food is handled”, Health and Safety Executive, 26 April, www.hse.gov.uk/food/chilled.htm.
HSE (2011h) “Struck by something (e.g. sharp knives or falling objects)”, Health and Safety Executive, 29 September, www.hse.gov.uk/food/struckby.htm.
HSE (2011i) “Prevention of dust explosions in the food industry”, Health and Safety Executive, 1 June, www.hse.gov.uk/food/dustexplosion.htm.
HSE (2011j) “Work related stress – together we can tackle it”, Health and Safety Executive, 11 October, www.hse.gov.uk/stress.
HSE (2011k) “Occupational asthma and rhinitis”, Health and Safety Executive, 26 July 2011, www.hse.gov.uk/food/asthma.htm.
HSE (2011l) “EH 40/2005 Occupational exposure limits”, 2nd edit., Health and Safety Executive, HSE Books, Sudbury, Sussex, England, ISBN 978 0 7176 6446 7. Available online at www.hse.gov.uk/pubns/priced/eh40.pdf.
HSE (2011m) “Registration, Evaluation, Authorization and restriction of Chemical substances (REACH)”, Health and Safety Executive, 10 November, www.hse.gov.uk/reach/.
HSE (2011n) “Dermatitis”, Health and Safety Executive, 11 October, www.hse.gov.uk/food/dermatitis.htm.
HSE (2011o) “Noise regulations”, Health and Safety Executive, 18 November, www.hse.gov.uk/noise/regulations.htm.
HSE (2011p) “Five steps to risk assessment”, Health and Safety Executive, INDG163(rev3), June. Available online at www.hse.gov.uk/pubns/indg163.pdf.
HSE (2011q) “Risk management”, Health and Safety Executive, 11 October, www.hse.gov.uk/risk/.
HSE (2011r) “Safe work in confined spaces”, Health and Safety Executive, INDG258, September. Available online at www.hse.gov.uk/pubns/indg258.pdf.
HSE (2012) “Injury statistics”, Health and Safety Executive, 13 January, http://www.hse.gov.uk/food/statistics.htm.
HSE (2013a) “Workplace transport”, Health and Safety Executive, 6 April. Available online at http://www.hse.gov.uk/food/transport.htm.
HSE (2013b) “Falls from height”, Health and Safety Executive, 6 April. Available online at http://www.hse.gov.uk/food/falls.htm.
HSE (2013c) “Packaging machinery – in all manufacturing industries”, Health and Safety Executive, 6 April. Available online at http://www.hse.gov.uk/food/package.htm.
HSE (2013d) “Roll cages and wheeled racks – Manual handling”, Health and Safety Executive, 6 April, http://www.hse.gov.uk/food/roll-cages-wheeled-racks.htm.

HSE (2013e) “Moving food and drink. Manual handling solutions for the food and drink industry", March. Available online at http://www.hse.gov.uk/pubns/priced/hsg196.pdf.

HSE (2013f) “Working platforms (non-integrated) on forklift trucks”, Guidance Note PM28 (4th edit.), Health and Safety Executive, April, http://www.hse.gov.uk/pubns/pm28.htm.

HSE (2013g) “Sound solutions for the food and drink industries. Reducing noise in food and drink manufacturing.” HSG 232. Available online at http://www.hse.gov.uk/pubns/priced/hsg232.pdf.

ISO (2006) “Safety of machinery. Safety-related parts and control systems – Part 1: General principles for design”, EN ISO 13849–1, International Organization for Standardization, Geneva.

OSHA (2003) “OSHA 2003–2008 Strategic Management Plan”, United States Department of Labor (www.osha.gov/StratPlanPublic/strategicmanagementplan-final.html).

OSHA(2012) “OSHA’s Cooperative Programs”, http://www.osha.gov/dcsp/compliance_assistance/index_programs.html.

Peters, M.S., Timmerhaus, K.D. and West, R.E. (2003) “Plant design and economics for chemical engineers”, 5th edit., McGraw Hill, New York, ISBN 0-07-119872-5, pp. 29–40.

PUWER (2011) “Simple guide to the Provision and Use of Work Equipment Regulations 1998”, Health and Safety Executive, September. Available online at www.hse.gov.uk/pubns/indg291.pdf.

Regulations (1992) “The Manual Handling Operations Regulations 1992”, Statutory Instrument No. 2793, HMSO, London. Available online at http://www.legislation.gov.uk/uksi/1992/2793/introduction/made.

Regulations (1994) “The Electrical Equipment (Safety) Regulations 1994”, Statutory Instrument No. 3260, HMSO, London. Available online at www.legislation.gov.uk/uksi/1994/3260/regulation/1/made.

Regulations (2005) “The Control of Noise at Work Regulations 2005”, Statutory Instrument No. 1643, HMSO, London. Available online at www.legislation.gov.uk/uksi/2005/1643/contents/made.

Regulations (2006) “Electromagnetic Compatibility Regulations 2006”, Statutory Instrument No. 1449, HMSO, London. Available online at www.legislation.gov.uk/uksi/2006/1449/introduction/made.

Regulations (2008) “The Supply of Machinery (Safety) Regulations 1992”, Statutory Instrument No. 1597, HMSO, London. Available online at www.legislation.gov.uk/uksi/2008/1597/contents/made. The 2008 Machinery Regulations were amended in 2011 (see www.legislation.gov.uk/uksi/2011/2157/made/data.pdf). For a guide to the application of the corresponding European Directive, see Fraser (2010).

RIDDOR (2012) “RIDDOR – Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1995”, Health and Safety Executive, undated, www.hse.gov.uk/riddor/.

Ritchie, I. and Hayes, W. (1998) “A guide to the implementation of the ISO 14000 series on environmental management”, Prentice Hall, New Jersey, ISBN 0-13-541097-5, Chapter 11

Chapter 8
Protecting the Environment

C.G.J. Baker and H.M.S. Lababidi

8.1 Introduction

Environmental issues are becoming of increasing concern to industry as a whole and, naturally, food manufacturing is not exempt. Although the industry can be regarded as a low-level polluter by many standards, there are significant opportunities for improving its environmental performance. Section 8.2 addresses some of the more pertinent issues.

The International Organization for Standardization (ISO) has published a number of standards concerned with environmental assessment and improvement (the ISO 14000 series). These standards are described in Sect. 8.3 and, where appropriate, reviewed in relation to food manufacturing. At the core of these is ISO 14001, "Environmental management systems—Requirements with guidance for use". This sets out the central requirements for an environmental management system (EMS) against which an organization is audited for ISO certification (registration). This standard is discussed from a food-industry perspective in Sect. 8.3, which is based in part on a report prepared by the Leatherhead Food Research Association, now Leatherhead Food International. The authors are very grateful to this organization for granting permission to quote freely from this report.

In the developed countries at least, planning permission will not be granted to build any food factory unless a detailed and plausible environmental impact assessment has been undertaken. This chapter sets out the necessary background that will need to be assimilated by the project team to facilitate this exercise. This includes the main sources of pollution that may be generated directly and indirectly by the factory (the Appendix is very useful here) and how they can be minimized. Coverage of the ISO 14000 environmental standard has also been included as it provides a widely accepted protocol for monitoring, recording and progressively reducing the environmental impact of the factory. Thus, it may be desirable to include in the list of project objectives that, once operational, the factory should achieve ISO 14001 certification. This could be to comply with (or help establish) company policy or to help expedite the planning process.

C.G.J. Baker (✉) • H.M.S. Lababidi
Chemical Engineering Department, College of Engineering and Petroleum,
Kuwait University, P.O. Box 5969 Safat, 13060 Kuwait
e-mail: christophergj.baker@gmail.com; haitham.lababidi@ku.edu.kw

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_8,

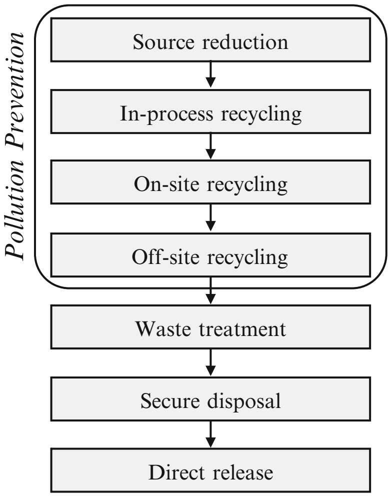


Fig. 8.1 The waste management hierarchy

8.2 Elements of Environmental Pollution Relevant to the Food Industry

8.2.1 Introduction

The following topics, discussed briefly below, are of general concern to the food-manufacturing industry: air pollution, mainly as a result of energy consumption and transportation, water pollution, and waste generation. For further in-depth guidance on these topics, the reader should consult one of the many environmental textbooks available (e.g., Nazaroff and Alvarez-Cohen 2001a, b, c).

Environmental problems cannot be solved unless hard data are available that quantify the nature and scale of the problem. These should be obtained by means of an environmental audit for existing factories or an environmental impact assessment for proposed factories. The former is based on plant measurements, equipment specifications and engineering estimates. The latter relies on projections provided by those with in-depth experience in operating similar plants. Both will provide the following information: (1) the types of waste produced, (2) the quantities of waste produced, (3) details of where in the process the wastes are produced, and (4) what causes them to be produced. This information will not only form the basis of an action plan to reduce emissions but will also provide the baseline against which future improvements will be judged.

The following hierarchy of approaches to reducing emissions of all categories is widely accepted:

1. Eliminate or reduce the emissions.
2. Reuse or recycle the waste materials.
3. Use an end-of-pipe technique to clean up the emissions.

This is consistent with the requirements of the US Pollution Prevention Act of 1990 (http://epw.senate.gov/text/envlaws/PPA90.pdf) illustrated in Fig. 8.1.

Thus, the best solution to any environmental problem is to "design it out," i.e., to eliminate or significantly reduce its impact. If this is not feasible, reuse or recovery are the next best options, where this is appropriate. Reuse is defined as "the use of waste material generated in one process directly in a second process without significant treatment or processing" (Nazaroff and Alvarez-Cohen 2001c). A typical food industry example of this is the conversion of waste from a human-food manufacturing process into animal feed. Recycle, "the regeneration of product from waste material following significant reprocessing," is typified by reworking in which a small fraction of off-spec material is blended back into the main production process and thereby incorporated into acceptable product. Neither the safety nor the quality of the final product is affected by this procedure but it does add to costs. Finally, end-of-pipe processes should be regarded as a solution of last resort, as, in many cases, they do not solve the problem but simply shift it to another area. Thus, chemical and biological water treatment processes generate considerable quantities of sludge that have to be disposed of in an acceptable manner.

8.2.2 Air Pollution

Unlike other industry sectors, food manufacturing is not a major polluter of the atmosphere. However, there are certain aspects that should be born in mind. These relate primarily to energy use and transportation. It is also necessary to consider indoor air quality within the factory, as this is vital for the production of safe and wholesome foodstuffs.

The principal sources of energy used within most food factories are natural gas and electricity. Natural gas is the preferred fuel because it is cleaner burning than either oil or coal. It is employed primarily within the boiler house to raise steam for operations such as retorting, pasteurizing, indirect drying, process heating, and space heating, to name but a few. It is also used directly as a fuel in, for example, baking ovens and direct-fired dryers.

Electricity is widely used for powering refrigeration plant, mixers, pumps, fans, conveyors, packaging machines, etc., and for lighting, and general-purpose use.

8.2.2.1 Combustion of Carbonaceous Fuels

The combustion of all carbonaceous fuels, including natural gas, generates carbon dioxide, the most predominant of the "greenhouse" gases that are claimed by most scientists to be primarily responsible for global warming. Concerns over the long-term impact of global warming have prompted many national governments to adopt fiscal measures to encourage energy conservation. A major driving force for this is to enable them to meet their obligations under the United Nations Framework Convention on Climate Change—the Kyoto Protocol (http://unfccc.int/resource/docs/convkp/conveng.pdf). By way of example, the UK introduced several such measures. The Climate Change Act 2008 (http://www.legislation.gov.uk/ukpga/2008/27/contents) contained "legally binding" targets to reduce greenhouse gas emissions by 34 % in 2020 and at least 80 % by 2050 (relative to the 1990 baseline). It also formulated interim 5-year budget reductions (relative to the 1990 baseline) as follows: 2008–2012: 22 %; 2013–2017: 28 %; 2018–2022: 34 %; 2023–2027: 49 % (DECC 2012). In 2010 (the latest year available at the time of writing), UK emissions of all greenhouse gases with allowance for trading (see below), was 593.9 $MtCO_2e$. This figure was 23.0 % below the base year emissions of 770.8 $MtCO_2e$.

As an aid to reaching its Kyoto targets, the UK government also introduced the Climate Change Levy with effect from 1st April 2001 (http://www.legislation.gov.uk/uksi/2001/838/contents/made). This is a tax on the use of energy in industry, commerce and the public sector. However, companies in energy-intensive industrial sectors can enter into agreements with the government through their trade associations that provide for an 80 % reduction in the levy if they meet challenging targets for increasing energy efficiency and/or reducing carbon emissions. Many UK companies in the food and drink sector have signed up to such a commitment.

Other examples of relevant legislation include an enhanced capital allowance scheme (http://www.eca.gov.uk/), in which qualifying investments in energy-saving equipment can be fully written off in 1 year, and the Integrated Pollution Prevention and Control (IPPC) Directive (http://ec.europa.eu/environment/air/pollutants/stationary/ippc/index.htm). Emissions trading is also viewed as a key instrument in the drive to reduce greenhouse gas emissions. The UK scheme was launched in

2002 and the European Union initiative came into effect on 1 January 2005. Under this scheme, participating companies are allocated a specific number of allowances, each of which represents the emission of 1 tonne of CO_2 equivalent. Companies that succeed in reducing emissions can sell their surplus allocations at the prevailing market price to companies that cannot meet their allocation targets. Wikipedia (2012) provides a comprehensive description of the scheme, together with its strengths and weaknesses.

The combustion of fuels also gives rise to “criteria” pollutants, which, in the USA, are regulated under the Clean Air Act 1970. These criteria pollutants are carbon monoxide (CO), oxides of nitrogen (NO_x), ozone (O_3), sulfur dioxide (SO_2), particulate matter (PM), and lead (Pb). Of these, ozone, a secondary pollutant formed by photochemical reactions in the atmosphere involving NO_x and VOCs (volatile organic compounds), is perhaps the most problematical. State and local authorities are required to monitor the concentrations of these pollutants and, where they don’t meet the national ambient air quality standard (NAAQS), to prepare and file plans outlining how they intend to make progress towards complying with the law. In such non-attainment areas, the only practical means of achieving the NAAQS is to reduce emissions.

For planning purposes, the emission rates of criteria (and other) pollutants can be estimated by means of air pollutant emission factors; examples of their use are given in Nazaroff and Alvarez-Cohen (2001b). Standard values of these factors are maintained by the US Environmental Protection Agency in a series of documents known as AP-42, which can be downloaded from http://www.epa.gov/ttn/chief/ap42/index.html. Chapter 9 of AP-42 is devoted to the food and agricultural industries. It contains flowsheets for a number of food-manufacturing processes that illustrate where VOC and PM emissions are commonly encountered.

Natural gas is a relatively clean fuel—hence its preferred use in food factories. It has a low sulfur content and therefore SO_2 emissions are minimal. NO_x production is comparable to that of other fuels. However, a lack of proper maintenance may result in incomplete combustion and the undesirable generation of substantial quantities of CO, carbonyls, aromatic compounds, and soot (Nazaroff and Alvarez-Cohen 2001b).

8.2.2.2 Electricity Use

In the developed countries, electrical power will normally be purchased from the local generating company. In order to minimize CO_2 emissions in particular, as well as to reduce costs, every effort should be made to conserve its use by operational means including energy management systems and through the purchase of high-efficiency equipment including lighting and motors.

In remote regions, where supplies are limited, or where economics dictate, it may be worthwhile installing a combined heat and power (CHP) system to produce electricity, hot water and steam (Wallin 1997). This type of system, which is discussed in some depth in Chap. 17, uses steam generated in a boiler to drive a turbine to produce electricity. Excess steam and condensate can be used for process- and space-heating purposes and surplus power sold back to the grid. The overall thermal efficiency of such systems can be significantly higher than those of separate generating systems and steam-raising plant. However, each case needs to be evaluated on its own merits.

8.2.2.3 Other Greenhouse Gases

According to DECC (2012), carbon dioxide accounted for 84 % of the UK’s greenhouse gas emissions on a global warming potential basis in 2010. The emissions of other gases included in the Kyoto protocol were methane (7.0 %), nitrous oxide (6.2 %), hydrofluorocarbons (2.4 %), sulfur hexafluoride (0.12 %), and perfluorocarbons (0.03 %). The agricultural sector accounted for

44 % and 80 % of methane and nitrous oxide releases, respectively. Food manufacturing would undoubtedly have been responsible for some leakage of hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) as these are widely used as refrigerants. Care should therefore be taken to minimize losses and recover any redundant gases. Refrigerants, including those that are responsible for depleting the ozone layer and whose use is therefore restricted under the Montreal Protocol (http://www.unep.org/ozone/pdf/Montreal-Protocol2000.pdf), are discussed further in Chap. 15.

8.2.2.4 Indoor Air Quality

Adequate control of indoor air quality (IAQ) is vital in order to protect the health of the workers and the safety of the products produced in the factory. Thus care should be taken, for example, to ensure that combustion products are properly vented outside and away from the factory, and that particulates, VOCs, and microorganisms, etc., are not allowed to accumulate within it. Reducing and controlling emissions and adequate ventilation should all be considered. In high-risk areas of the factory more stringent methods are required. These may include physical isolation from the rest of the factory, positive air pressures to prevent the ingress of contaminated air, and/or the use of HEPA (high-efficiency particulate air) filters.

8.2.2.5 Vehicular Transport

The food industry is heavily reliant on the movement of raw materials, packaging, and other supplies into the factory and on the delivery of finished products to their ultimate retail outlets. In most cases this will involve road transport and therefore due consideration should be given to the effects of a relatively large number of vehicular movements into and out of the factory.

At the local level, care should be taken to ensure that excessive vehicle movements do not constitute a nuisance to neighbors, particularly during the night. Despite progressive improvements in emission standards over the years, motor vehicle exhausts continue to be a persistent source of CO, NO_x and VOCs and, in the case of diesel engines, particulates. Every effort should therefore be made to minimize emissions by optimum scheduling of journeys, regular maintenance, and driver training.

8.2.3 Water Pollution

Many food factories are prodigious users of water. Hence the quality of the incoming supply and outgoing effluent are important considerations. Water that is used as an ingredient of the food or drink or comes into direct contact with it must comply with appropriate legislation and meet any quality standards that are set by the company for the particular product in question. This may or may not necessitate treatment of the water on-site. In factories involving the processing of fruit and vegetables and in dairies, breweries and meat-processing plants, large quantities of water are used for washing purposes. The resulting wastewater may contain high levels of total solids, biological oxygen demand (BOD), cleaning agents, and pesticide residues. Depending on consent levels, this water may require some pretreatment on-site before it is discharged into the public sewer or into a watercourse. Chapter 18 deals with effluent treatment.

Water is a valuable commodity and the costs of supply and waste treatment are significant in most regions. Its use should therefore be reexamined periodically with a view to reducing where possible consumption and the level of contamination. Water reuse and recycling schemes are often cost effective and protect the environment—see Chap. 17.

8.2.4 Solid and Liquid Wastes

The food industry produces a variety of solid and liquid "wastes" that must be reused, recycled or otherwise disposed of. Such wastes may include outdated raw materials and product, wastes resulting from animal processing (skin, blood, unusable body parts, fat and grease, etc.) and vegetable processing (skins, stalks, peelings, etc.), off-spec processing waste, packaging waste, and so on. Given present-day pressures on landfill sites, and the rising cost of this method of disposal, it should be regarded as a last resort. This section focuses on means of reducing these wastes. For further guidance, see, for example, CCFRA (2000) and Zall (2004).

The quantities of waste generated by factories producing similar food products often vary widely. It may be possible to achieve substantial cost savings as well as benefiting the environment by reducing the levels of such wastes to values comparable to those achieved by best-practice producers. The first step in this process is to conduct an audit in order to generate the necessary data required to formulate an effective waste reduction plan. The Michigan Department of Environmental Quality (MDEQ 2010) has posted a useful document on the Internet that provides a number of valuable suggestions for reducing waste from food factories. Examples include:

- Use a "first-in, first-out" inventory policy for raw materials to prevent them exceeding their shelf life.
- Buy in bulk to reduce container waste (Do not buy excessive material that would spoil, however).
- Store raw vegetables in appropriate reusable containers to prevent dehydration and spoilage.
- Conduct energy and water audits to help determine ways to conserve these valuable resources.
- Identify problem solid wastes and, where possible, procedures for recycling them.
- Minimize packaging wastes and, if possible, package products in recyclable or reusable containers.
- Institute a hazardous waste collection program.
- Donate nonperishable and unspoiled perishable food to worthy recipients. Alternatively, where possible, process discarded human food into animal food, or send it for rendering (liquefied fats, solid meat products, and grease) or composting (most organic material except meat or bones, fatty foods, diseased plants, plants treated with weed killer, and pet waste).
- Develop a storm water pollution prevention policy.

As part of any waste minimization plan, attempt to minimize the quantity of rework generated by means of suitable process modifications and/or improved control. Although much of this material is eventually incorporated into the food product, reworking does add to costs and disrupts production flows.

Most waste generated by food factories is nonhazardous in the legal sense (i.e., it is not subject to the provisions of the Resource Conservation and Recovery Act in the USA that apply to hazardous waste). However, solvents and other chemicals, cleaning fluids, etc., should be disposed of in accordance with the regulations.

8.3 ISO 14000

8.3.1 Introduction

The International Organization for Standardization (ISO) was founded in 1947. Located in Geneva, Switzerland, it is an independent, privately funded organization, which has as its members the standards organizations from more than 100 countries (typical examples include ANSI representing

Table 8.1 The ISO 14000 series of standards

ISO 14001 and 14004: Environmental management systems

ISO 14001: Requirements with guidance for use (2004)
ISO 14004: General guidelines on principles, systems and support techniques (2004)

ISO 14010 Series, ISO 19011: Guidelines for environmental auditing

ISO 14015: Environmental management—Environmental assessment of sites and organizations (2001)
ISO 19011: Guidelines for auditing management systems (2011)

ISO 14020 Series: Environmental labeling

ISO 14020: Environmental labels and declarations—General principles (2000)
ISO 14021: Environmental labels and declarations—Self-declared environmental claims (Type II environmental labeling) (1999, amended 2011)
ISO 14024: Environmental labels and declarations Type I environmental labeling—Principles and procedures (1999)

ISO 14030 Series: Environmental performance evaluation

ISO 14031: Environmental management—Environmental performance evaluation—Guidelines (1999)

ISO 14040: Life cycle assessment

ISO 14040: Environmental management—Life cycle assessment—Principles and framework (2006)
ISO 14041: Environmental management—Life cycle assessment—Goal and scope definition and inventory analysis (1998)
ISO 14042: Environmental management—Life cycle assessment—Life cycle impact assessment (2000)
ISO 14043: Environmental management—Life cycle assessment—Life cycle interpretation (2000)
ISO 14044: Environmental management—Life cycle assessment—Requirements and guidelines (2006)
ISO 14047: Environmental management—Life cycle assessment—Examples of application of ISO 14042 (2003)
ISO 14049: Environmental management—Life cycle assessment—Examples of application of ISO 14041 to goal and scope definition and inventory analysis (2000)

Note: The table includes only current standards, as of March 2012

the USA and BSI representing the UK). Its function is to promote the development of international manufacturing, trade, and communications standards.

ISO standards are international voluntary consensus standards, developed through a system of technical committees and working groups representing industry, government and other interested parties. They have legal and regulatory standing within any particular country only if they are formally adopted by that country. Compliance with any standard by an organization is purely voluntary.

A series of major environmental disasters (the chemical and radiation releases at Bhopal and Chernobyl, and the Exxon Valdez oil spill off the Alaska coast), followed by the 1992 Rio Declaration on Environment and Development (http://www.un.org/documents/ga/conf151/aconf15126-1annex1.htm), were key factors in initiating work on developing the ISO 14000 series of international environment standards in 1993. Other factors included interest by GATT (General Agreement on Tariffs and Trade), now superseded by the World Trade Organization (WTO), and the resounding success of ISO 9000, the international quality standard. Subsequently published as a series of individual standards (see below), ISO 14000 provides organizations with a proactive generic structure for initiating, improving, or sustaining environmental management and improvement programs.

8.3.2 Structure of ISO 14000 Series

The ISO 14000 series consists of the individual standards listed in Table 8.1. Of these, the standards relating to environmental management systems and environmental auditing are the most important. Brief outlines of each of the standards are given below. For an in-depth coverage of the standards, the reader is recommended to consult Ritchie and Hayes (1997) and Piper et al. (2003).

8.3.2.1 ISO 14001 and 14004: Environmental Management Systems

These two documents form the core of the series. Between them, they set out the basic requirements of a model environmental management system (EMS). ISO 14001 was first published in 1996 and updated in 2004. The principal differences between the two versions are conveniently summarized in two Web sites (CSA Undated; Praxiom 2011). These include numerous changes in the wording that clarify the text of ISO 19001:1996 and in some cases change its emphasis. However, as discussed below, two clauses relating to evaluation of compliance and management review, do result in additional requirements.

ISO 14001 sets out the central requirements for an EMS against which an organization is audited for ISO certification/registration (see below). It does not require the organization to achieve an absolute standard of environmental performance. However, it does require commitments in the policy statement to comply with all relevant environmental laws and regulations, and to continually improve its environmental performance. The standard also suggests (but does not require) a linkage with the management of occupational health and safety. The use of best available technology (BAT), subject to technical and economic feasibility, is also encouraged.

ISO 14004:2004 contains general guidance for formulating an EMS based on the following six underlying principles that require an organization to:

- Define and adopt an environmental policy.
- Ensure organizational commitment to environmental improvement.
- Formulate a plan with objectives and targets to fulfill the environmental policy.
- Implement the plan by developing the capabilities and resources to achieve the environmental policy, objectives, and targets.
- Measure, monitor and evaluate environmental performance.
- Review and continually improve the EMS.

8.3.2.2 ISO 14010 Series and ISO 19011: Environmental Audits

ISO standards 14010, 14011 and 14012, published in 1996, provided the original guidance for conducting an environmental management system (EMS) audit. These standards have now been superseded by ISO 19011 (see below). An EMS audit is defined as “the systematic, documented verification process of objectively obtaining and evaluating audit evidence to determine whether specified environmental activities, events, conditions, management systems, or information about these matters conform with audit criteria”. ISO 14010 described the general principles on which an EMS audit is based (Ritchie and Hayes 1997):

- Basing the audit on objectives described by the client.
- Utilizing an audit team that is independent of the activities they audit and utilizing an auditor who meets the qualification criteria set out in ISO 14012.
- Using due professional care by the auditor to maintain confidentiality and adequate quality assurance.
- Using systematic procedures for conducting the audit.
- Developing audit criteria, evidence and findings.
- Ensuring that the process provides the desired level of confidence in the reliability of the audit findings and conclusions.
- Providing an adequate report of findings.

These principles were elaborated on in ISO 14011, which also described a framework for conducting the audits. Finally, ISO 14012 listed qualification criteria for both internal and external environmental auditors. These include education, on-the-job training, work experience, personal attributes and skills, maintenance of competency, and due diligence.

In 2002, the individual auditing standards for quality (ISO 10011-1, 10011-2, and 10011-3) and environmental management systems (ISO 14010, 14011, and 14012) were replaced by a unified standard ISO 19011, "Guidelines for quality and/or environmental management systems auditing". This approach has several advantages. It:

- Facilitates the integration of quality and environmental management systems;
- Allows a single audit of both systems, thereby saving both time and money;
- Provides the certification/registration bodies with a uniform approach;
- Recognizes more explicitly than earlier auditing guidelines that it is not possible to set uniform competence criteria, which are applicable to all kinds of situation;
- Combines into a single standard the descriptions of the management of audit programs and the conduct of individual audits.

ISO 19011:2002 was updated in 2011. The new standard "Guidelines for auditing management systems" is broader in scope than its predecessor and provides more generic guidance. This was necessary because a number of new management system standards had been published since 2002. It contains four principal sections: Principles of auditing, Managing an audit program, Performing an audit, and Competence and evaluation of auditors. In addition, Annex A provides guidance on the required knowledge and auditor skills for a number of specific disciplines, including environmental management, and Annex B provides additional guidance for auditors planning and conducting audits. The principal differences between ISO 19011:2002 and ISO 19011:2011 have been summarized in IRCA (2011).

ISO 14015, "Environmental management—Environmental assessment of sites and organizations (EASO)," was published in 2001; it is still current. This standard was designed to provide a structured approach for a company to follow when assessing the environmental issues and associated business consequences of its own sites and organizations or those of potential acquisitions. It is anticipated that the likely users of the standard will include industry, past, present and possible future users of particular sites, and organizations with a financial interest in the industry or site (e.g., banks, insurance companies, investors, and site owners). ISO 14015 requires an assessment of the impact of all media (air, water, and waste).

8.3.2.3 ISO 14020 Series: Environmental Labeling

Environmental- or eco-labeling is recognized as providing the end-user with information relating to the environmental impact of a particular product. A large number of different labeling schemes have been promulgated by state and national governments and multi-national bodies such as the EU. These have been described in some detail in a 1998 EPA report entitled "Environmental labeling issues, policies, and practices worldwide" (http://www.epa.gov/epp/pubs/wwlabel3.pdf). Unfortunately, this report, although extensive, does not include coverage of food manufacturing.

Eco-labeling schemes can be classified as first-party (labels produced by companies to support the environmental attributes of their own products), or third-party, which are issued by independent organizations after verifying the claims. Labels can be positive, negative or neutral. Positive labels certify that the product possesses certain environmental attributes. Negative labels warn consumers about harmful or hazardous ingredients (such labels are often mandatory). Finally, neutral labels summarize environmental information, which can be used by consumers to aid them in their purchasing decisions. The guiding principles and practices underlying third-party environmental labeling are listed in Chapter 1 of Ritchie and Hayes (1997).

The diversity of national eco-labeling schemes and the lack of uniform criteria have limited their use, particularly in cross-border situations. As a result, ISO developed the 14020 series standards that established a common basis for the award of eco-labels. Three types of labeling scheme were recognized:

- Type I—a multi-attribute label developed by a third-party.
- Type II—a single-attribute label developed by the producer.
- Type III—an eco-label awarded on the basis of a full life cycle assessment.

Type I and Type II labels are covered by ISO 14024:1999 and 14021:1999, respectively. Type III labels are discussed in a Technical Report ISO/TR 14025 "Environmental labels and declarations—Type III environmental declarations," published in 2006.

Eco-labeling is seen to have a number of benefits (http://www.iisd.org/business/markets/eco_label_benefits.asp):

- Informing consumer choice. (Eco-labeling is an effective way of providing consumers with the information they need to make informed purchasing decisions on the basis of environmental factors.)
- Promoting economic efficiency. (Eco-labeling is generally cheaper than regulatory controls.)
- Stimulating market development. (Consumers can have a direct impact on promoting the supply of more environmentally friendly products.)
- Encouraging continuous improvement (A dynamic market for eco-labeled products provides a strong incentive.)
- Promoting certification/registration. (A strong market demand for eco-labeled products will stimulate active involvement in environmental improvement programs.)
- Assisting in monitoring. (Environmental claims can be monitored more easily.)

8.3.2.4 ISO 14030 Series: Environmental Performance Evaluation

ISO 14031, which provides guidelines for Environmental Performance Evaluation (EPE), was published in 1999. EPE is defined by ISO as a "process to facilitate management decisions regarding an organization's environmental performance by selecting indicators, collecting and analyzing data, assessing information against environmental performance criteria, reporting and communicating, and periodically reviewing and improving this process." The standard provides a management tool for helping organizations introduce a cost-effective, non-bureaucratic indicator framework, where the link between management effort and actual improvement is clarified.

The ISO 14030 series provides organizations with an effective means of producing and assembling reliable and verifiable multi-site data relating to their environmental performance. It is likely to become an increasingly important tool in satisfying reporting requirements on carbon dioxide and other greenhouse gas emissions.

Technical Report ISO/TR 14032 (1999) provides a range of examples of the application of EPE in different organizations such as manufacturing and service companies, government agencies, and nongovernmental organizations.

8.3.2.5 ISO 14040 Series: Life Cycle Assessment

It has long been recognized that a cradle-to-grave approach to assessing the environment impact of a particular product, which takes into account all aspects ranging from raw material extraction to product disposal, is superior to an assessment of the manufacturing process alone. There are two reasons for this approach. First, individual operations could be made cleaner and more efficient simply by displacing the pollution elsewhere. In other words, there was no net benefit to the environment in this approach. Secondly, traditionally engineers had concentrated their efforts on improving the efficiency of individual units while neglecting to evaluate and optimize the performance of the overall production and use sequence. In many cases, this latter approach could result in a further enhancement of benefits.

Early life cycle assessment (LCA) studies concentrated mainly on energy and raw materials use but were later extended to include air and water emissions and solid wastes. The foundations of current LCA methodology in which the analysis was split into three main stages were set out at the 1990 SETAC conference in Vermont. The three stages are:

1. Inventory. The data describing the system are collected and converted into a standard format.
2. Interpretation. Physical data from the inventory are related to observable environmental problems.
3. Improvement. The system is modified to reduce or ameliorate the observed environmental impacts.

In order to optimize the environmental performance of the system, the three stages are repeated in a cyclic manner to evaluate improvements and identify any side effects that might occur.

The series contains three principal standards (ISO 14041:1998, ISO 14042: 2000, and ISO 14043: 2000), which, between them, describe the different stages of the life cycle assessment program. A commentary on the evolution and interrelation of the standards has been published by Marsmann (2000). A relevant example of life cycle assessment relating to an evaluation of the environmental benefits of refillable beverage containers can be seen on http://refillables.grrn.org/content/environmental-benefits. Two reports complement the standards. These are ISO/TS 14048 (2002), "Environmental management—Life cycle assessment—Data documentation format," and ISO/TR 14049 (2000), "Environmental management—Life cycle assessment—Examples of application of ISO 14041 to goal and scope definition and inventory analysis".

8.3.2.6 Other Relevant ISO Standards and Reports

Other standards not included in Table 8.1 are worthy of note. The ISO 9000 series on quality management is very similar in its approach to ISO 14000. Both are generic management system standards that can be applied to any organization, large or small, in business, commerce, public administration, or government, regardless of the product produced or service provided. ISO 9000 is accepted worldwide and its success encouraged the development of the environmental standards. As noted above, ISO 9001 and 14001 now share a common auditing procedure as described in ISO 19011.

ISO 14050 "Environmental Management—Vocabulary," republished in 2009, was produced to provide a coherent approach to the description of environmental activities and terminology, and to contribute to a common understanding of environmental management terms. The bilingual (English and French) standard is intended for use by those using and implementing the ISO 14000 standards as well as translators and technical writers in the field of environmental management.

Finally, ISO/TR 14062 "Environmental management—Integrating environmental aspects into product design and development" (2002) was produced to enable organizations identify the likely effects on the environment of their future products and make effective decisions during the design and development stages to improve their environmental performance.

8.3.3 ISO 14001 Certification

ISO 14001 certification (the preferred European terminology), or registration (in the USA), is the process in which an approved external body audits a company's Environmental Management System and gives written assurance that it complies fully with ISO 14001 requirements. It does not imply that the company is a non-polluter or that its products, services, or production processes are environmentally friendly. The time required to initiate an effective EMS is typically 6 months to 2 years. This is normally followed by a pre-audit to iron out any weaknesses before the official audit is conducted.

The ISO procedures can be followed by a company that wishes to become certified or as the basis for formulating an internal, uncertified EMS. The company's decision on whether or not to proceed with ISO 14001 certification will undoubtedly be based largely on commercial considerations. These include:

- An enhanced company image with the public, customers, and government organizations.
- Increased market share, particularly if customers require ISO 14001 certification as a prerequisite to doing business (c.f. ISO 9001).
- Cost savings through waste minimization, pollution prevention and increased efficiency.

Peglau and Baxter (2007) concluded that in the decade since ISO 14001 was published in 1996; the standard has been used as the basis for some 110,000 environmental management systems in 138 countries worldwide. Moreover, in 2006, a total of around 20 million people were employed in ISO 14000-certified organizations. The authors described a large number of examples ranging from cruise liners to chimney sweeps. Only one example of a food and drink manufacturer was cited; a whisky distillery in Scotland.

8.4 Guide to the Preparation of an Environmental Management System

8.4.1 Introduction

An Environmental Management System (EMS) will assist organizations to focus on ways to improve their environmental performance. It will be of particular value to companies that:

- Are required to comply with environmental legislation;
- Recognize that their environmental performance constitutes a liability;
- Lack the time and/or resources to put their environmental affairs in order;
- Are able to relate their environmental objectives to their business objectives.

An EMS is basically a continual cycle of planning, implementing, reviewing, and improving. It assists management to identify the principal causes of environmental problems and subsequently to eliminate them. It helps companies save money by:

- Making a product right the first time rather than having to perform a lot of rework later;
- Preventing pollution rather than being forced to clean it up afterwards.

Naturally, it involves costs as well as benefits. The costs include employee time, staff training, and, possibly, outside consultancy. The likely benefits are improved environmental performance, improved legislative compliance, new customers, increased manufacturing efficiency, improved employee morale, reduced training effort for new employees, and an enhanced image with both the general public and the regulators.

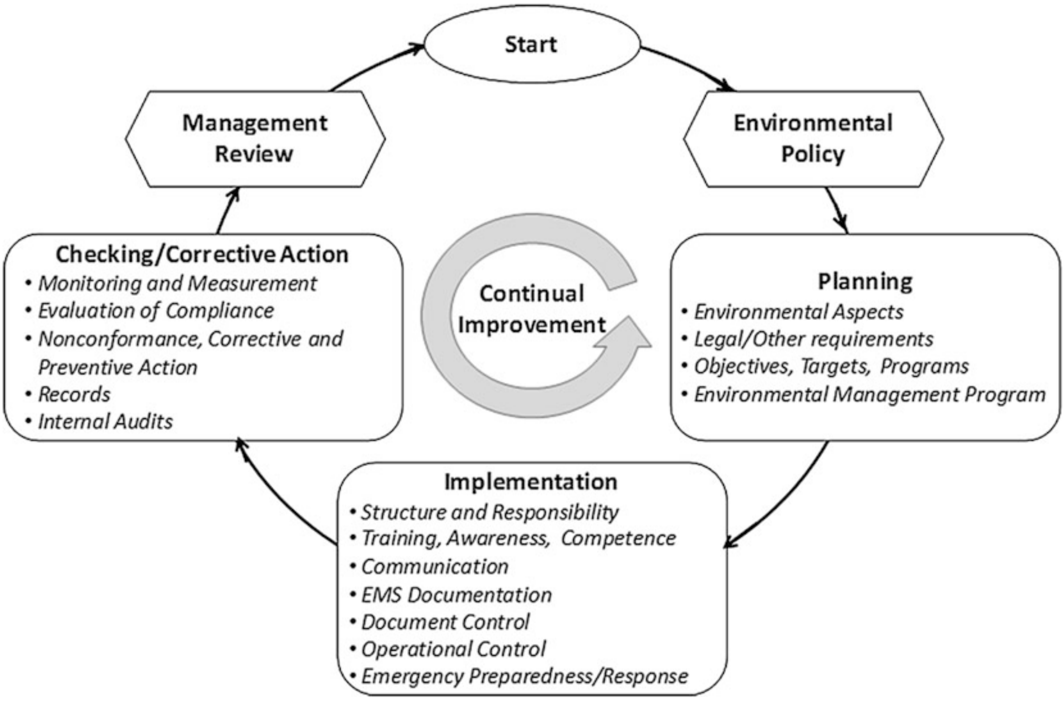


Fig. 8.2 Key elements of ISO 14000 EMS

ISO 14001 shares many features in common with the earlier British standard, BS 7750 "Specification for Environmental Management Systems" (now withdrawn). Leatherhead Food Research produced a report (Whitman 1994) specifically aimed at assisting food manufacturers prepare an EMS that complies with BS 7750. The present section and the Checklist set out in the Appendix draw heavily on this report. However, the material has been updated to bring it into line with ISO 14001 and 14004 and new legislation. This section is designed to be read in conjunction with, not instead of, these standards.

8.4.2 Structure of the EMS

Figure 8.2 illustrates the different components of the ISO 14001 Environmental Management System. These are discussed briefly in the paragraphs that follow.

Subsections in this chapter corresponding to those in ISO 14001 and ISO 14004 are listed in Table 8.2.

8.4.3 Initiation

8.4.3.1 Commitment

The first step in formulating any EMS is to obtain management commitment at the highest level in the company. The decision, for example, to seek ISO 14001 certification will affect not only the operation

Table 8.2 Corresponding subsections in this chapter, ISO 14001 and ISO 14004

Heading	This chapter	ISO 14001	ISO 14004
Commitment	8.4.3.1	–	4.1.1, 4.1.3
Initial environmental review	8.4.3.2	–	4.1.4
Environmental policy	8.4.4	4.2, A2	4.2
Environmental aspects	8.4.5.1	4.3.1, A3.1	4.3.1
Legal and other requirements	8.4.5.2	4.3.2, A3.2	4.3.2
Objectives, targets, and program(s)	8.4.5.3	4.3.3, A3.3	4.3.3
Environmental management program(s)	8.4.5.4	4.3.4, A3.4	4.3.3.2
Resources, roles, responsibility, and authority	8.4.6.1	4.4.1, A4.1	4.4.1
Competence, training, and awareness	8.4.6.2	4.4.2, A4.2	4.4.2
Communication	8.4.6.3	4.4.3, A4.3	4.4.3
Documentation	8.4.6.4	4.4.4, A4.4	4.4.4
Control of documents	8.4.6.5	4.4.5, A4.5	4.4.5
Operational control	8.4.6.6	4.4.6, A4.6	4.4.6
Emergency preparedness and response	8.4.6.7	4.4.7, A4.7	4.4.7
Monitoring and measurement	8.4.7.1	4.5.1,A5.1	4.5.1
Evaluation of compliance		4.5.2, A5.2	4.5.2
Nonconformity, corrective action, and preventive action	8.4.7.2	4.5.3, A5.3	4.5.3
Control of records	8.4.7.3	4.5.4, A5.4	4.5.4
Internal audit	8.4.7.4	4.5.5, A5.5	4.5.5
Management review	8.4.8	4.6, A6	4.6

and public perception of the site in question but also other sites owned by the company. Managers will need to give due consideration to the additional requirements for manpower and financial (capital and operating) resources that result from making the environment an organizational priority. They will also absorb the need to include environmental considerations in product and process development and to view environmental problems as opportunities for improving manufacturing operations.

It will obviously be necessary to appoint an able and qualified project manager to spearhead the required operational and cultural changes. The person in question should have the necessary authority, effective project management skills, and an understanding of the organization. He/she should be a "systems" thinker, perhaps an ISO expert, and should have enough time to commit to the EMS. One of his first tasks will be to prepare a budget and schedule. The necessary staff time, training requirements, need for consultancy, and material and equipment requirements all need to be taken into consideration. The next step involves building a project team. This should include representatives of the following key functions: operations, services, maintenance and engineering, finance, public relations, marketing and sales, etc. It may also be appropriate to include external parties such as contractors and suppliers.

8.4.3.2 Initial Environmental Review

Companies that do not have an existing EMS should undertake a preparatory review to not only establish the status of their current environmental programs and systems but also to evaluate the effectiveness of their structure, procedures, policies, environmental impacts, and training programs. Specifically, it should set out to identify:

- Legal requirements
- Significant environmental aspects (elements of an organization's activities, products or services that result in changes, adverse or beneficial, to the environment)
- Existing management practices and procedures
- Feedback from previous incidents.

In assessing the environmental aspects, the following specific issues should be considered:

- Controlled and uncontrolled emissions to atmosphere
- Controlled and uncontrolled emissions to water, including sewers
- Solid and other wastes
- Contamination of land
- Use of land, water, fuels and energy, and other natural resources
- Discharge of thermal energy, noise, odor, dust, vibration, and visual impact
- Effects on specific parts of the environment including ecosystems.

The appended checklist, adapted from Whitman (1994), provides a useful basis for conducting this part of the review.

The preparatory review will form the basis of the subsequent Environmental Policy (see below). It should therefore be documented for reference purposes and perhaps subjected to internal review. Future updating of the report can yield valuable trend data and aid planning and budgeting. It is suggested that the preparatory review should be included in the ISO 14001 documentation as an informative annex.

8.4.4 Environmental Policy

The Environmental Policy Statement (EPS) is key to the success of the overall program. It should be prepared on the basis of the information contained in the preparatory review and should reflect the long-term goals and wider aspirations of the whole company. Because of its importance, senior management should take overall responsibility for this document, which should ideally be signed by the CEO. The contents of the statement, which must be made available to the public, will form the basis of the company's environmental objectives and targets.

The Policy should cover all aspects of a site's operation, including products, activities, and services. It should make reference to the following:

- Its appropriateness in relation to the nature, scale, and environmental impact of the business.
- Dedication to a program of continual improvement in environmental performance.
- Compliance with current and future environmental legislation and other requirements that have a direct bearing on how the organization handles environmental issues.
- The setting and reviewing of environmental objectives and targets.
- The need to document, implement, maintain and communicate the Policy throughout the company (i.e., to both employees and contractors).

A number of other considerations to aid in the preparation of an EPS are set out in Sect. 4.2 of ISO 14004. These include guiding principles, the organization's mission, core values and beliefs, relations with interested parties, coordination with quality, health and safety policies, and local or regional considerations.

An example of an Environmental Policy Statement can be seen on page 36 of Ritchie and Hayes (1997).

8.4.5 Planning

8.4.5.1 Environmental Aspects

Section 4.2.1 of ISO 14001 requires that a register of environmental aspects be compiled and maintained in order to determine which have or could have a significant (positive or negative)

Table 8.3 Selected Web sites detailing environmental legislation

Web site URL	Comments
http://www.epa.gov/	US Environmental Protection Agency homepage
http://www.epa.gov/lawsregs/index.html	Introduction to US laws and regulations
www.law.cornell.edu/wex/Environmental_law	Overview of US environmental legislation. Links to Energy Law, Land Use, and Natural Resources
http://unfccc.int/resource/docs/convkp/conveng.pdf	Kyoto Protocol
http://www.environment-agency.gov.uk/	UK Environment Agency homepage
http://www.legislation.gov.uk/	UK legislation homepage
http://www.eea.europa.eu	European Environment Agency homepage

impact on the environment. This is subsequently used to prepare objectives and targets. The initial review can be used as the foundation for preparing the register. The company should consider effects that arise, have arisen, or might arise as a result of:

- Normal operating conditions, including shutdown and start-up
- Abnormal operating conditions
- Incidents, accidents and potential emergency situations

Procedures are required to examine and evaluate all relevant environmental aspects and to include in the register those that are considered to be significant. The 2004 standard requires that these procedures should also be implemented. In considering significance, both the direct and indirect effects of the company's activities, products and services, both present and future, should be assessed and documented. The evaluation of indirect effects should include all those over which the company has direct control and all those over which it could reasonably be expected to have influence.

It should be borne in mind that the food and drinks industry must approach environmental problems from two directions. Firstly, it has a duty to avoid contributing to any deterioration in the environment and to strive to improve it. Secondly, food-manufacturing operations can only be carried out safely under hygienic conditions. Enhancement of the local environment is therefore of direct benefit to the industry.

8.4.5.2 Legal and Other Requirements

In most parts of the world, environmental pollution is regulated by an increasing body of legislation. It is important to recognize that ISO 14001 does not in itself commit certified companies to adhere to specific standards of emission control. Rather, the company's Environmental Policy commits it to complying with all relevant laws and regulations. It should therefore demonstrate that the relevant regulations are known, have been considered for relevance, and, where appropriate, are complied with.

ISO 14001 therefore requires that companies set up and use a mechanism to ensure that they have full and ongoing access to present and future legislation pertaining to the environmental aspects of their activities, products, and services. As laws do change periodically, the EPS should also show that checks are made to ensure that relevant requirements of the law are fulfilled at all times. Official government sites on the Internet are perhaps the most convenient source of information on environmental legislation. Table 8.3 lists some useful Web sites.

In the UK, the Environmental Protection Act 1990 consolidated and reinforced many previously established statutory nuisances and this forms the basis of much of the legal protection of the environment. Under English law at least, it has been established over the years that the following lines of defense do not hold:

- The nuisance was there before the plaintiff
- All reasonable care had been taken
- Public good
- The business was well suited to the locality
- The nuisance was the action of a contractor.

8.4.5.3 Objectives, Targets, and Programs

The environmental objectives and targets of the site need to be consistent with the Environmental Policy and to provide for continual improvement of the identified environmental aspects over a period of time. Where possible, the objectives should be quantified and measurable. Targets should include a timescale. The views of relevant interested parties should be considered before objectives and targets are identified.

The objectives must include compliance with all relevant legislation, and a statement that the site management will strive for improvements that will deliver a level of performance equivalent to that from the economically viable application of the best available technology. Due to the diversity of food and drinks manufacturing processes, it is not possible to set uniform performance standards across the industry.

The 2004 standard requires that programs be set up to try and achieve the objectives.

8.4.5.4 Environmental Management Programs

In order to achieve the multiple objectives that may arise from an analysis of all the significant environmental impacts, it will be necessary to formulate a number of programs, one for each main objective. Each program may consist of:

- An outline of the problem
- The objective, and targets to be achieved
- Designation of staff responsible
- The means by which the objective and targets are to be achieved
- Control and reporting procedures.

In assessing the environmental impact of new products and processes, it will also be necessary to include in the program provision for:

- Dealing with changes as projects progress
- Corrective actions that may be needed and, if required, checking to ensure that they are effective.

8.4.6 Implementation and Operation

8.4.6.1 Structure and Responsibility

Sufficient resources should be provided to establish, maintain and improve the EMS. Key jobholders need to have sufficient authority and training to carry out their responsibilities, which should be fully defined in their job descriptions. Their position in the corporate management structure should also be formalized and should be consistent with the importance of their duties. The reporting structure should ensure that there is no impediment that would restrict the effectiveness of the performance of these duties. Deputies should be appointed as appropriate and a system of emergency cover defined.

The individual appointed by management to take full responsibility for the efficient implementation of the Environmental Management System should:

- Have the necessary experience, status and authority.
- Have adequate resources to implement and effectively operate the EMS. Such resources should include human resources, necessary skills, and appropriate budgets.
- Have direct reporting access at the highest levels in the company in relation to environmental issues.
- Be capable of giving high priority to environmental issues regardless of other short-term commitments.
- Be responsible for initiating periodic reviews of the EMS.

No Environmental Management System will be successful unless a sufficient number of properly qualified and trained staff is available to check compliance and to take appropriate action in the event of emergencies.

8.4.6.2 Training, Awareness and Competence

All staff should receive appropriate training in the importance of the Environmental Management System and their role in ensuring compliance with the required standards. They should also be made aware of the benefits of improved environmental performance to the company. Competence and training records should be maintained.

8.4.6.3 Communication

The company is required to develop a single system to collect all information, ideas and opinions, both internal and external, about its environmental program and its environmental effects. These communications may be made in writing, verbally (meetings) or by telephone. All communications need to be acknowledged, analyzed and, when appropriate, considered for further action. If it has been decided to communicate significant environmental aspects to parties outside the company, a suitable mechanism should be established and maintained.

8.4.6.4 Documentation

A manual should be prepared that documents all the elements of the Environmental Management System in a concise and logical manner. This will include: the scope of the EMS, the environmental policy, details of the organization and personnel, the environmental effects register, the objectives, targets, and work program, as well as the control, audit and review, and emergency procedures. Provision for the testing of emergency plans, simulation exercises, mock incidents, etc., should be included in the system.

The manual should describe the relation between the system elements and guide the reader to associated documentation, and other aspects of the EMS. A procedure will be required to review and update the manual as required and responsibility for this should be specified.

8.4.6.5 Control of Documents

A documented procedure, with assigned responsibility for its implementation, will be required for the systematic control of all the documents that together form the Environmental Management System. This procedure should ensure that all relevant documents are identifiable, properly authorized, dated, and available as current versions to all who need them, and that outdated documents are removed from use.

8.4.6.6 Operational Control

Properly documented operating procedures and controls relating to all relevant operations and activities are required to enable an organization meet its obligations as defined by its policy, objectives and targets. Responsibility for the planning, execution and checking of these tasks should be defined and required performance standards stipulated. ISO 14001 stipulates that such operational procedures and controls are required when their absence could lead to deviations from the Environmental Policy, objectives and targets. Where appropriate, these procedures and controls should be communicated to suppliers and contractors and steps taken to ensure that they are fully complied with.

Changes to existing processes and procedures should be checked for environmental implications and subject to approval.

8.4.6.7 Emergency Preparedness and Response

Breaches of regulations may occur from time to time due to mistakes, ignorance and lack of forethought. When legally required to do so, the company should inform the authorities when errors are made, collaborate with them to rectify the problem, and to learn from the error.

A procedure should therefore be drawn up setting out a deliberate course of action to be taken in the event of an incident occurring. This procedure should be widely disseminated to those within the company who need to know. It should include plans both for immediate action to alleviate the effects of the incident and provision for the company to review the incident dispassionately after the event to ensure that lessons are learned, procedures are really improved, and operators are encouraged to come forward quickly and honestly when things go wrong. It is important that no one is less than honest about environmental problems, and potential problems, with those who should be informed about them.

An emergency procedure should be drawn up to cover all site operations. This procedure, which must be used in the appropriate circumstances, may be based on a review of the site to identify potential hazards and their risk rating. Specific actions may be worked out for the more significant risks. Some of the points that need to be considered are:

- The desirability of establishing a Crisis Management Team (CMT).
- Definition of the circumstances that require convening the CMT.
- Membership of the CMT; job titles, emergency contact numbers, alternates, responsibilities.
- Contact procedures for the CMT—who contacts them and how.
- Information and facilities required by CMT.
- Emergency service contacts.
- Site plan—with hazards identified and contingent risks.
- Action plan for off-site incidents presenting a risk to factory operations (e.g., fire in neighboring premises).

- Incident Audit.

A written procedure for preparing an Incident Audit should be drawn up. Such an audit should be undertaken automatically after any incident in which the CMT is involved, after a breach of regulations, and after any incident that the manager responsible judges might reasonably have resulted in a major problem. The Incident Audit may be required to investigate:

- What happened
- What was done to clear up after the incident
- Why the problem occurred
- What could be done to prevent a recurrence (procedures, people, training, and equipment).
- Whether there are other operations susceptible to similar hazards
- Who should take what action, and within what time scale.

8.4.7 Checking and Corrective Action

8.4.7.1 Monitoring and Measurement

Section 8.4.5.1 of ISO 14001 requires that documented procedures be prepared for monitoring and recording on a regular basis those process characteristics that may have an impact on the environment. These procedures should define:

- The information to be obtained, and the way in which it is to be handled and retained.
- The monitoring procedures used, including details of the accuracy, care and maintenance of the measuring equipment, and the calibration procedures and records to be retained.
- Procedures for periodically evaluating compliance with relevant legislation.
- Acceptance criteria and action to be taken when results fall outside these criteria.
- The way in which previous monitoring results are assessed when monitoring systems are found to be malfunctioning.

The duties of competent personnel to monitor the environmental impact of the company’s processes, products and activities should also be defined.

8.4.7.2 Evaluation of Compliance

This is a new requirement set out in ISO 14001:2004. It requires a certified company to establish, implement and maintain procedures that will be used from time to time to determine how well it conforms with both legal and other environmental requirements. It also requires the company to record the results of its findings.

8.4.7.3 Nonconformity, Corrective Action and Preventative Action

Competent staff of appropriate standing in the organization should be designated to take responsibility for investigating cases of noncompliance with the specified environmental standards. Procedures should be established and used for conducting the investigation, planning corrective action and, when agreed and authorized, carrying out, documenting and checking the effectiveness of the changes.

8.4.7.4 Control of Records

Records must be kept to demonstrate the effectiveness of the Environmental Management System. According to ISO 14001:1996, these records should include:

- The policy, objectives and targets as they have changed with time and circumstances.
- Records of communications received and actions arising.
- Monitoring records, which should show, in particular, how targets and objectives have been met.
- Records of audits, and policy reviews.
- Incident records.
- Training records.
- Records of surveillance of supplier and contractor performance.
- Records of performance checks on monitoring and test equipment.

In contrast, ISO 14001:2004 does not list the records that an organization should keep. Rather, it states that the records that are kept should demonstrate that the environmental management requirements are being met and that the organization is in compliance with the new standard.

8.4.7.5 Internal Audit

Periodic internal audits are required to check that the EMS is achieving the standard defined by the organization's Environmental Policy. Audits should be planned so that all areas and aspects of the system are audited at a frequency commensurate with their environmental significance. They should be carried out by auditors who are skilled, experienced and, as far as possible, independent of the functions being audited; specialist assistance should be made available when required. The results of all internal audits should be recorded.

Audit procedures should be documented and designed to meet the requirements of the function or area being audited. The procedures should cover checks on documentation and on operations and results. The audit report should cover:

- Compliance with the EMS requirements
- The effectiveness of the system in meeting the defined objectives and targets
- Results of actions recommended in previous audits
- Conclusions and recommendations

Those responsible for the area or function audited should be required to take timely action as recommended.

8.4.8 Management Review

Periodic reviews of the whole system and of appropriate parts are required in order to enable top management to assess its effectiveness in achieving the aims set out in the Environmental Policy Statement and the continuing suitability and relevance of the Policy and the site objectives and targets. The new standard is far more explicit in the requirements in this respect than the original version in that it specifies both the required inputs and outputs. The inputs should include: audit results, changes in environmental aspects, communications/complaints from external parties, legal changes, previous management reviews, status of previous corrective and preventative actions, follow up actions, and recommendations for improvement. The review should also document decisions/actions that change the environmental policy, objectives or targets, and improve the organization's EMS. These outputs should confirm the organization's commitment to continuous improvement.

8.5 In Conclusion

Protecting the environment is becoming increasingly important in today's world. This chapter has focused on those aspects, which are of prime concern to the food manufacturing industry. The Environmental Management System described in ISO 14001 provides a sound basis for ensuring that all legislation is fully complied with and that opportunities for improved environmental performance are systematically identified and implemented.

Appendix: Checklist to Aid in the Preparation of a Preparatory Review and a Register of Environmental Effects for Food Factories

A.1 Introduction

The objectives of preparing the checklist are: to help to identity opportunities for improvement that are urgent, easy, or cost-effective; to assist in providing quantitative data to be used to set targets and objectives; and to provide a snapshot picture of the total environmental situation at the company at one point in time as the basis for future assessments of progress.

To obtain the most benefit, information about trends in the data should be derived wherever possible. These can often be expressed as the variation with time of such ratios as energy or water consumption per tonne of production. For example, consider the case where the energy consumption per tonne of custard powder produced has risen over 3 successive years. In these circumstances, some positive ideas are required to support the suggestion that a 10 % reduction target could be achieved over the following year.

In most factories, production tonnages and the cost of services (energy, water and effluent, etc.) are available from the accounting system and may be used to construct trend information. It may not be easy or even possible to break down historical data to allocate costs to individual production lines but, if this can be done, it will provide valuable information.

The following check list is set out in question and comment form with the intention that it may be used by a company as a guide when carrying out an Environmental Impact Assessment on a proposed new factory or an Initial Environmental Review or a register of environmental effects on an operating facility. It may also be used by an auditor to aid in the preparation of an environmental audit. Certain questions have legal implications. In such cases, examples of relevant legislation applying within the UK are cited for illustrative purpose. Undoubtedly, similar legislation will have been enacted in many other jurisdictions. Note that the list of citations should not be regarded as being complete and up-to-date.

A.2 Some General Considerations

A.2.1 Documentation

- Does the company hold all necessary planning and operating permits?
- Is there a central register of these documents?
- Are they all complied with?
- Has a register of all environmental legislation affecting the factory and its operation been compiled and are procedures in place to keep it up to date?

A.2.2 Process Considerations

Considering both the factory operations as a whole and also each product line individually:

- Are the production processes the best environmental choices?
- Are there good reasons why the current processes are preferred?
- Are the measuring, monitoring and accounting procedures in place to evaluate current levels of consumption and loss, and the benefits to the company of any improvement?
- Can action be taken to improve yields and to reduce waste?
- Do the factory records provide any evidence of changes in yields and waste levels over the past 3 years?
- Is the level of downgrading and recycling justified? Can action be taken to improve it?
- Have standards changed over the past 3 years?
- Is there a system for appraising the environmental impact of new or modified products and processes?
- Is information on yields, wastes, etc., available in production records? An analysis of trends will be useful for planning purposes.
- Has the best environmental choice of process been made? This is a very open question; the answer will be influenced in part by answers to subsequent questions in the checklist but it may also need investigation of patent and reference literature.
- Are full hazard assessments for all materials and processes used available?
- Are process flow diagrams and mass balances for each operation available? These will help in identifying emissions and losses.

A.2.3 Emergencies

- Have appraisals of fire, spillage and explosion risks in the factory been undertaken? (Control of Major Accident Hazards Regulations 1984, Amended 2009).
- Are there contingency plans to deal with spillages, fires and breakdowns? Have these been tested?
- Is there an adequate communication system for use in emergencies? Has this been tested?

A.2.4 Factory Site

- Is the factory located in an area suitable for the manufacture of good-quality food—free from off-odors, airborne dust, pests and drainage problems? If not, are adequate additional systems always in place to deal with anticipated problems?
- Are past uses of the site documented, together with information about that past use, e.g., contaminated ground/water?

A.3 Air

A.3.1 Global Warming

Contributors to global warming are: all energy sources, some refrigerants, combustion gases such as CO_2, CO, oxides of nitrogen.

- Is there a more energy-efficient route to the product?
- Can overall factory energy consumption be reduced?
- Is there a case for CHP (a combined heat and power plant) or a new boiler house or the use of pressurized hot water heating?
- For each product, has energy consumption/tonne changed over the last 3 years? Have energy reduction targets been set? Are they being achieved?
- Have all the points from the last factory energy survey been actioned?

Inefficient combustion contributes disproportionately to global warming. Savings in energy consumption/tonne are at the same time cost-effective.

Uncontrolled production of methane (a potent greenhouse gas) by anaerobic digestion is hazardous. If it is produced deliberately in a digester it should be burned off in circumstances where the heat of combustion can be usefully recovered.

Oxides of nitrogen arising during combustion may be minimized by proper selection and maintenance of burners.

A.3.2 Ozone Layer

The main factory involvement will be due to the use of ozone-layer-depleting HCFCs in refrigeration and air-conditioning plant. Under the provisions of the Montreal Protocol, the production of CFCs ceased in 1995; for all practical purposes the production of HCFCs is scheduled to cease in 2020 (2015 in the EU). Some commercial alternatives to HCFCs are now available and others are being developed. The use of halons in firefighting equipment, which also contributed to the depletion of the ozone layer, has also been banned. (Environmental Protection (Control on Ozone-Depleting Substances) Regulations 2002).

- Have refrigeration and air conditioning plants using HCFCs all been identified? Does this include transport inwards and outwards?
- Is there a plan to replace HCFCs? Are HCFC losses controlled and are waste and redundant HCFCs recovered? It is illegal to vent HCFCs to the atmosphere. The same is true for any HCFC-replacement refrigerants unless they have been certified as not being harmful to the atmosphere.

A.3.3 Acid/Alkali Emissions

Oxides of nitrogen and sulfur are most likely to arise from coal- or oil-fired boiler plant. Stack gas levels should be checked. There will be some SO_2 discharge from handling raw materials such as fruit juices and pulps.

There may be some loss of ammonia if it is used as refrigerant.

A.3.4 Ground-Level Ozone

The substances that will have an effect on ground-level-ozone levels are volatile organic compounds (VOCs) and NO_x. In food manufacture, the principal VOC emissions are likely to be carbon dioxide from fermentation processes, but there may also be some loss of solvent (hydrocarbons, ketone) from extraction, printing and painting operations.

A.3.5 Other Aspects

Other aspects warranting consideration are: dust, smoke, radioactive substances and radiation. None of these is a general problem for the food and drink industry, but dust emissions may occur from factories producing or handling powders due to filter failures. (See Sect. A8.2)

A.4 Water

Water availability, quality and discharge are all important to food manufacturers because large amounts of water may be used. Part of the water will form a constituent of the food.

Environmentally, it is desirable to control water consumption and to minimize pollution of watercourses.

- Is water consumption monitored? What water-conservation measures are in place? What recycling initiatives are in operation?
- Has water consumption per tonne of product altered over the last 3 years?
- What are the main uses of water?
- Is water available at constant quality and in sufficient volume? Are there fears about future changes in quality, availability or price? Are you in regular contact with your water company, receiving reports on quality and advance notice of engineering operations that are likely to affect the quality or continuity of supply?
- Are products likely to be tainted by trace contaminants from water? If so, is there a permanent quality monitoring system?
- Is river water used? Is it treated? Is it returned to the source and, if so, is it kept separate from other effluents?
- If it is returned to the source, does it comply with consent conditions?
- Are precautions taken to avoid contamination of watercourses by spillages of hydrocarbons etc., and by run-off from firefighting operations?

A.5 Land and Resources

A.5.1 Asbestos

- Has asbestos been used in construction work on site? Is there a program for its safe removal and disposal using licensed contractors? Is there a procedure to safeguard all food production while the clearance program is in hand? (Asbestos (Licensing) Regulations 1983, Amended 1998; Control of Asbestos at Work Regulations 2002; Control of Asbestos in Air Regulations 1990).

A5.2 Hazardous Organisms

Does the company use pathogens or other potentially hazardous organisms? Are there licensed procedures to contain, handle and dispose of them? (Trade Effluents (Prescribed Processes and Substances) Regulations 1989, 1992)

- Are there procedures to dispose of food wastes containing pathogens or other potentially hazardous organisms?

A.5.3 Hazardous Wastes

(Control of Pollution Act 1974, Amended 1989; Pollution Prevention and Control Act 1999; Control of Pollution (Special Waste) Regulations 1980, Amended 1993; Collection and Disposal of Wastes Regulations 1988; Controlled Waste Regulations 1992, Amended 1993)

- Is there a procedure for segregating any waste that may have become contaminated so that it can if necessary be disposed of as hazardous waste?
- Are there procedures to minimize the use of poisonous metals such as lead, cadmium and mercury and to avoid their loss to drain?

A.5.4 Radioactive Wastes

These are not likely to occur in the food industry.

A.5.5 Nonhazardous Wastes

- Is there a management policy to minimize solid and liquid wastes? Have procedures for auditing solid and liquid waste discharges been established? Is there evidence of a change in waste quality or quantity over the last 3 years?

Liquid Wastes

- Is the factory's liquid waste consent to discharge to sewer or watercourse complied with at all times? (Control of Pollution (Discharges into Sewers) Regulations 1976).
- If not, what are the reasons for noncompliance and what action is being taken to rectify the situation?
- What quantity of organic solids is being discharged to drain?
- Has the ratio of solids to production tonnage changed over the last 3 years? Could action be taken to reduce the organic load discharged to drain?
- Are all outside storage tanks and silos bunded?
- Could the solids content of the factory effluent be reduced by cost-effective additional primary treatment on site?
- Is there an adequate fat trapping provision on site?
- Is the pH of the effluent monitored and kept within consent conditions? Is the temperature of the effluent monitored?

Solid Wastes

- Are solid wastes being monitored for quantity and composition?
- Are good housekeeping programs in place to minimize factory losses?
- Are wastes disposed of by an authorized contractor? (Environmental Protection Act 1990).
- Could any improvement be made in waste disposal procedures, for instance by composting or sale as animal food?
- Is the on-site waste storage site satisfactory in terms of hygiene, size and general appearance?
- Is there likely to be a future problem of waste disposal?

A.5.6 Habitats

- Does the company endeavor to carry on its operations with the minimum loss of habitats?
- Is it appreciated that there is potential conflict with the requirements of the Food Safety Act if rodents, insects, etc., are left undisturbed?

A.5.7 Radioactive Substances

(Radioactive Substances Act 1993; Radioactive Substances (Substances of Low Activity) Exemption Amendment Order 1992)

- Does the company have a register of radioactive substances in use on site (thickness meters, density gauges, laboratory instruments)? Has a manager been appointed to maintain necessary records and procedures?
- Is there a natural source of radioactivity on site? Is this regularly monitored?

A.6 Energy Consumption

There is a national undertaking to make significant reductions in CO_2 emissions; all companies should be seen to be playing their part in achieving this target by controlling and reducing energy consumption. (Pollution Prevention and Control Act 1999; Pollution Prevention and Control (England and Wales) Regulations 2006, Amended 2007; Climate Change Levy 2001).

- Is energy consumption being monitored? What energy initiatives are in operation? How has energy consumption per tonne changed over the last 3 years? Is there a manager with special responsibility for energy control? What achievements have there been over the last 3 years? Are they cost-effective?
- Is coal or oil used as fuel on site? Have steps been taken to minimize any contamination arising? (Control of Smoke Pollution Act 1989; Clean Air Act 1993).

A.7 Materials Inward

This term is used to include not only raw materials that will be used to manufacture the food products but also such items as machinery, packaging, cleaning materials and the packaging that may be associated with these items. All of these may need to be considered for direct or indirect environmental impact.

A.7.1 Raw Materials

- Are there procedures to examine raw materials on receipt to determine their suitability and to identify any special need for pretreatment or segregation before use? (Food and Environment Protection Act 1985; Pesticides (Maximum Residue Level in Crops, Food and Feeding Stuffs) (England and Wales) (Amended) Regulations 2008; Food Safety Act 1990).

- Are raw material losses investigated? Are there procedures to maximize raw material utilization?
- Are sources of raw materials and specifications considered from an environmental point of view?
- Is there an effective pest-control procedure? How is this managed with respect to its potential environmental impact?
- Are regular checks carried out on pesticides, herbicides, mycotoxins, heavy metals, and radioactivity to ensure that these comply with legal or company standards?
- Is consideration given to stock exploitation, overfishing, etc., when sourcing raw materials?

A.7.2 Packaging

- Are environmental issues considered when specifying packaging?
- Would alternative packaging materials be more environmentally acceptable without impairing product safety and quality at point of sale and point of use?
- Have returnable, reusable and recyclable packages been considered for each raw material and product?
- Do competitors use similar packaging specifications to your own? If not, are their packages considered to be more environmentally acceptable?

A.7.3 Nonfood Deliveries

- Is consideration given to the environmental implications of the purchase of nonfood materials? These may include HCFCs in refrigeration equipment, the energy costs of running compressors, or the safe disposal of cleaning and disinfecting fluids?

A.7.4 Associated Packaging

- What steps are taken to ensure the return, reuse, or recycling of packaging materials?

A.8 Nuisance

The factory should play its part as a good neighbor and, as such, take action to blend into the neighborhood and not create a nuisance to those living in the vicinity. (Town and Country Planning Act 1990; Town and Country Planning (Assessment of Environmental Effects) (Amendment) Regulations 1990, 1994; Building Regulations 2010; Clean Air Act 1993).

- Does the factory participate in any local body to liaise with those living in the area?
- Are steps taken to limit the use of neighboring streets for parking by factory staff, visitors or delivery vehicles?
- Could other actions be taken to improve environmental practices within the factory or the public perception of the company as an environmentally aware and caring organization?

A.8.1 Visual

- Are the factory site and environs kept tidy? Is the factory maintained in a reasonable outward state of repair?

A.8.2 Dust and Odors

- Are dusts from factory operations kept to a minimum? Are dust-filter failures spotted and acted on at once? Is there a procedure for apologizing to neighbors and, if necessary, providing compensation when property is spoiled by dust escapes?
- Are sources of odors within the factory identified? Is action taken to minimize, contain, scrub, burn-off, or otherwise counteract odors? (Environmental Protection Act 1990).
- Is a record made of complaints about factory smells? Is this reviewed regularly and appropriate action taken?

A.8.3 Noise and Vibration

- Do neighbors complain about vibration, noise, or traffic levels? Are these complaints recorded? (Environmental Protection Act 1990).
- Is action taken to reduce and control noise, vibration, and traffic between the hours of 2200 and 0600?
- Do waiting lorries have to park outside the factory?
- Have all reasonable steps been taken to limit noise and vibration within the factory?

A.9 Finally

You must always think of ways of improving your environmental performance. This takes commitment, knowledge, and expertise.

You cannot be a good neighbor if you are not doing all you can to comply with the law.

References

CCFRA (2000) "Waste management in the food industry: An overview", Key Topics in Food Science & Technology—No. 2, Campden Food & Drink Research Association (now Campden BRI), Chipping Campden, Gloucestershire GL55 6LD, England.

CSA (Undated) "Summary of key changes between ISO 14001:1996 and ISO 14001: 2004", Canadian Standards Association Technical Committee on Environmental Management Systems, http://www.csagroup.org//repository/ca/Cdn%20Guidance%20on%2014001.pdf.

DECC (2012) "Statistical release: 2010 UK greenhouse gas emissions, final figures", Department of Energy and Climate Change, 7 February, http://www.decc.gov.uk/assets/decc/11/stats/climate-change/4282-statistical-release-2010-uk-greenhouse-gas-emissi.pdf.

IRCA (2011) "IRCA briefing note: ISO/FDIS 19011:2011—Guidelines for auditing management systems", International Register of Certificated Auditors, London, August, http://www.irca.org/Documents/press/2011/ISO%20FDIS%2019011%202011%20Briefing%20Note.pdf.

MDEQ (2010) "Food industry pollution prevention and waste reduction", Michigan Department of Environmental Quality, 2 July, http://food-hub.org/files/resources/Food%20Industry%20Pollution%20Prevention%20and%20Waste%20Reduction.pdf.

Marsmann, M. “The ISO 14040 family”, Int. J. Life Cycle Assessment, 2000, 5(6), 317–318.

Nazaroff, W.N. and Alvarez-Cohen, L. (2001a) “Environmental engineering science”, John Wiley & Sons, New York, Chapter 6, pp. 280–387.

Nazaroff, W.N. and Alvarez-Cohen, L. (2001b), ibid, Chapter 7, pp. 388–483.

Nazaroff, W.N. and Alvarez-Cohen, L. (2001c), ibid, Chapter 6, pp. 484–600.

Peglau, R. and Baxter, M. (2007) “A decade of ISO 14001”, ISO Management Systems, May-June, 13–21.

Piper, L., Ryding, S.-O., and Henricson, C. (2003) “Continual improvement with ISO 14000”, IOS Press, Amsterdam, The Netherlands, 367 pp.

Praxiom (2011) “ISO 14001 2004 vs. ISO 14001 1996”, Praxiom Research Group Ltd, Edmonton, Alberta, Canada, 22 December, http://www.praxiom.com/iso-14001-new.htm.

Ritchie, I. and Hayes, W. (1997) “A guide to the implementation of the ISO 14000 series on environmental management”, Prentice Hall, Englewood Cliffs, NJ.

Wallin, P.J. (1997) “Food Factory Design and Operation”, Chapter 17 in “Food Industries Manual”, 24th edit., (ed.) Ranken, M.J., Kill, R.C., and Baker, C.G.J., Blackie Academic & Professional, London, pp. 557–573.

Whitman, W.E. (1994) “BS 7750. The role of food factories in managing the environment. A guide to the preparation of an environmental management system”, Special Report, Leatherhead Food Research, Randalls Road, Leatherhead, Surrey KT22 7RY, England.

Wikipedia (2012) “European Union emission trading scheme”, Wikipedia, 22 February, http://en.wikipedia.org/wiki/European_Union_Emission_Trading_Scheme.

Zall, R.R. (2004) “Managing food industry waste: Common sense methods for food processors”, Blackwell Publishing Professional, Ames, IA.

Chapter 9
Control and Monitoring of Food-Manufacturing Processes

I. McFarlane

9.1 Introduction

This chapter begins with descriptions of the building blocks of control systems, which include the sensors for process parameters and product attributes, as well as the control modules, operator facilities and reporting devices. In the later parts of the chapter, methods for the incorporation of these building blocks in control schemes and information systems are reviewed, with special reference to system reliability and database management. In the final section, there is a guide for matching instrumentation and process equipment in specific forms of processing.

9.2 Instrumentation

Sensors may be categorized as follows:

- General purpose sensors for process conditions
- Sensors for humidity and moisture
- Chemical composition sensors
- Devices for measurement of size, shape, and color
- Devices for sorting and sensing of foreign bodies.

The first category differs from the others because sensing of process conditions is a common requirement in all sectors of manufacturing industry; food manufacturers can therefore take advantage of the economy of scale and degree of reliability associated with long and widespread use.

In all the other categories, not only are there the costs of developing or adapting sensors for particular applications, but there are also the delays and uncertainty associated with such developments. A lack of suitable in-line sensors was highlighted as far back as the mid-1980s (Wren 1985). Kress-Rogers and Brimelow (2001), Tothill (2003), Patel and Beveridge (2003) and Zhou and Therdthai (2012) provide comprehensive descriptions of current instrumentation and sensor technology. Despite the developments that have occurred in recent years, there is still much to be done. Measurement of food quality parameters in real time still largely remains an elusive goal.

I. McFarlane (✉)
School of Agriculture, Policy and Development, University of Reading, Agriculture Building, Whiteknights,
Reading RG6 6AR, UK
e-mail: i.d.mcfarlane@reading.ac.uk

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_9,

9.2.1 Sensors for Process Conditions

Sensors are needed in almost every process for temperature, pressure, mass, level, and flow. Thermocouples using welded junctions of standard metal alloys, with associated automatic compensation for cold junction temperature, are suitable for most food process applications. Thermocouples of any one type are interchangeable. When it is necessary to measure to within a few tenths of a degree, a platinum resistance thermometer (PRT) is recommended.

Downstream from processing there is a need to monitor temperature during food storage and distribution, and a range of "time-temperature" indicator systems are available for this purpose. Three types are described by Taoukis et al. (1991). Type 1 is a diffusion-based indicator, in which a mixture of fatty acid esters and phthalates diffuse along a porous wick to provide a visible critical temperature indication (CTI) for frozen foods or integrated time-temperature indication (TTI). Type 2 is based on a color change caused by a pH decrease on enzymatic hydrolysis of a lipid substrate, such as glycerine tricapronate; color changes continuously, and can be monitored by a colorimeter. Type 3 is based on the ability of disubstituted diacetylene crystals to polymerize through a lattice-controlled solid state reaction. The polymer is highly colored. Types 1 and 2 are activated by removal of a barrier at the time of application, but Type 3 is active from the time of assembly and needs to be stored at low temperature until use. Smolander et al. (2004) explored the effectiveness of time-temperature indicators in monitoring the quality of modified-atmosphere packaged broiler chicken cuts stored in under different temperature conditions. Several types of TTIs were tested in preliminary trials for their capability of indicating the microbiological and sensory quality of the chicken cuts. In subsequent trials, two TTIs, a Type 2 and a Type 3, were selected for further study. The results showed that the microbiological shelf life could be considerably improved by maintaining a low temperature representing an ideal, unbroken cold chain. For example, when the average storage temperature was lowered from 8.3 to 3.4 °C, the shelf-life of the chicken cuts more than doubled. There were good correlations between the product quality and the indicator color change. The authors therefore concluded that TTIs played a useful role in monitoring the quality of the chicken cuts.

Strain gauge transducers are used directly for pressure measurement, and provide the main sensing element in many pressure, mass, level and flow measuring systems. It is frequently necessary to interpose a diaphragm seal between the sensing element and the sensing position, to protect the element from corrosion and to provide a crevice-free sensing environment. Strain gauge transducers are used in load cells for vessel weighing or pack weighing, and pressure transducers can sometimes be used for measuring hydrostatic head. More positive level indication can be obtained using fixed-point capacitance or electro-optic sensors, or by continuous ultrasonic level sensors. Difficulties are frequently experienced with level sensors of all types due to the presence of agitators, to foaming or deposits, or to changes in density, viscosity, or electrical properties. Suppliers of instrumentation can usually advise on the most suitable sensor and extent of precautions necessary for a particular application. One technique designed for difficult applications uses capacitance sensing at radio frequencies (RF) of 15–500 kHz between an electrode suspended from the top of a vessel and the walls of the vessel. The very large difference in dielectric constant between air and most fluids or granules provides the principle of measurement.

The types of flowmeter in use in food operations are listed in Table 9.1. Air and gas flow measurement is readily achieved using various proprietary systems. A sharp-edged orifice plate in a circular pipe may be used, but orifice plates introduce a significant pressure drop and, if this is unacceptable, one of the standard forms of Venturi tube may be substituted. Axial flow turbine meters are widely used in batching, blending, and bottling systems. The nature of the fluid and the rate of flow both influence the calibration of turbine meters; if the meter is calibrated with the fluid in use it is possible to achieve repeatability of 0.1 % and an accuracy of 0.5 % of full scale.

Table 9.1 Types of flowmeter

Type	Applications	Characteristics
Turbine	Gas, low viscosity fluids	Wide dynamic range
Orifice plate	Gas	Suitable for fluid beds
Venturi	Gas	Low pressure drop
Variable area	Most gases and liquids	Visual readout
Vortex	Most gases and liquids	Minimum pressure drop
Positive displacement	Most fluids, including those with suspended solids	Accurate for dispensing
Ultrasonic	Most gases and liquids	Not suitable for two-phase flows
Magnetic	Most fluids	Nonintrusive, integrating
Coriolis	All	True mass flow

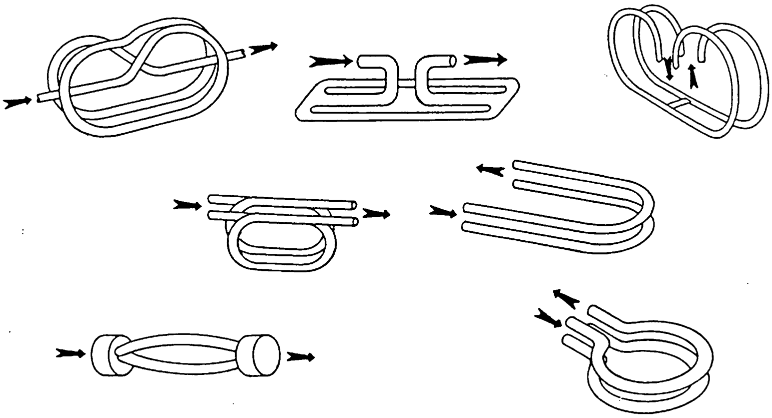


Fig. 9.1 Shapes of resonant tubes for Coriolis flowmeters (after Medlock and Furness 1990)

For fluids and slurries, the two most important methods of flow measurement in food applications are the magnetic flowmeter and the Coriolis force meter. Both are noninvasive, hygienic, and suitable for very wide ranges of flow. Coriolis meters are the only true mass flowmeters; magnetic flowmeters integrate the whole flow, but on a volumetric basis. Magnetic flowmeters are suitable for conducting fluids of low or moderate viscosity, and some meters incorporate an ultrasonic cleaning cycle. They are available for pipes from 3 to 2,000 mm diameter, and offer 1 % accuracy. True mass flow of nonconducting fluids such as chocolate liquor can be measured by Coriolis force meters, which measure the force required to give an angular acceleration to a mass moving in a radial direction. For a description of the Coriolis effect and its application in mass flowrate measurement, see Wikipedia (2012a, b). Medlock and Furness (1990) report ten different shapes in use for the vibrating element; seven of these shapes are illustrated in Fig. 9.1. The performance of Coriolis meters is very good in terms of range, repeatability, accuracy (typical 0.4 %), and stability, but they have the disadvantages of high pressure drop and sensitivity to external vibration. Two-phase flow also affects performance, which is degraded if there are any bubbles in the line. However, Coriolis meters do work well with homogenized mixtures including ice-cream.

The indirect "loss-in-weight" method of flow metering, by which flowrate is calculated from the reduction in weight of the supply vessel over a selected time, has the advantages of creating no obstruction, and of being without moving parts.

9.2.2 Measurement of Product and Process Attributes

9.2.2.1 Density, Viscosity, and Particle Size

Density, viscosity, and particle size are physical properties of special interest in food processing, partly because they are frequently associated with sensory evaluation. Accurate density measurement is needed for the standardization of milk, for gravity control in brewing and for solvent extraction control in edible oil refining, and these are all applications for one of the resonant tube styles of densitometer. For high viscosity fluids, a single-tube straight-bore density transducer has been developed. This is vibrated lengthways and isolated by flexible bellows to prevent errors due to thermal expansion or pipework stresses.

For sugar syrup concentration and other large-scale evaporation tasks, continuous multiple-effect evaporators offer savings in energy consumption. A density feedback controller can enable automatic stabilization. Mechanical vapor recompression gave large steam savings in the concentration of dextrose and fructose at the Cardinal, Ontario facility of Canada Starch. 13,500 l/h of liquid dextrose slurry were fed to a 4-effect evaporator operated at 93 °C. Vapor was returned at 0.46 bar and 82 °C to a centrifugal compressor, where it was compressed to 0.78 bar, raising the condensing temperature back to 93 °C. The compressor was used in combination with two evaporators, the first for dextrose and the second for fructose (at about 41 % solids). The lowered evaporation temperature prevented discoloration of the sugar solution.

The measurement of viscosity is far from trivial as many liquid and semi-solid foodstuffs are non-Newtonian in nature, i.e., their viscosity is a function of the shear rate. Methods for food viscosity measurement are reviewed by Bourne (2002), who stresses the significance of the Reynolds number. Flow patterns change from laminar to turbulent at Reynolds numbers greater than about 3,000, beyond which the effective viscosity increases rapidly with increasing shear rate. More recent texts devoted specifically to the rheology of foodstuffs have been written by Rao (2007) and Norton et al. (2011).

In some food processes, product quality is strongly dependent on particle size, particularly chocolate refining and coffee processing, while in spray drying operations droplet size sets the important ratio of exposed surface area to total mass. There is always a statistical distribution associated with particle size, and in some cases, such as flaked products, several parameters are needed to describe the important characteristics.

The Coulter principle, patented in the USA in 1953, is very widely used as the basis for particle sizing and counting in many sectors of industry. A dilute suspension of the particles is prepared in a solution of electrolyte. The suspension is drawn through an aperture, and a constant electrical current passed through the aperture between electrodes placed in the fluid on either side. When a particle passes through the aperture, the electrical resistance between the electrodes increases and a voltage peak is produced. The height of this peak is proportional to the volume of electrolyte displaced—i.e., the particle volume. More recently, particle size measurement by scattering of laser light has become feasible, and is used in chocolate refining. Samples have to be diluted to separate the particles, so that single-particle scattering equations can be applied. The concentration ranges over which low-angle laser light scattering can be used to measure particle size are described by Wedd (1993); the lower limit can be extended to 0.0001 mm (0.1 μm) by using information from light scattered at right angles to the laser beam.

9.2.2.2 Extrusion Conditions

Product temperature during extrusion is an example of a variable which is difficult to measure. In an extruder, a pattern of heating or cooling using water, steam, oil or coolants circulating in different sections of the barrel jacket is applied. The lack of direct measurement of conditions within the extruding mass makes it difficult to vary the production rate. Most extruders are therefore operated at a fixed throughput. This is not a serious restriction provided that the rate does not have to be matched to other equipment. In just a few instances, in the manufacture of composite confectionery products, for example, the extrusion rate is dictated by the rate of continuous production of base material. To match the production rates of machinery items whose outputs are continuously blended together can be difficult, and brief stoppages in any stream tend to cause a disproportionate loss in production. In such circumstances a central information facility performing online mass balance calculations is recommended.

9.2.2.3 Chocolate Temper

Cocoa butter is able to crystallize in different forms, and it is necessary to “temper” chocolate to promote crystallization in a stable polymorphic form. Chocolate temper meters are available, in which the cooling curve of a sample is plotted against time. If the fat is undertempered, with insufficient crystals of the stable form, the fat releases heat of crystallization after supercooling and a temperature increase is observed. Conversely, if the fat is overtempered, the decrease in temperature is scarcely interrupted. The optimum degree of temper depends on the arrangement of the plant, but a cooling curve corresponding to the preferred degree of crystallization can be readily selected. Tempering is required for all chocolate bars and chocolate-covered confectionery. The control of temper is described by Talbot (2009). Tempering treatment differs slightly for different chocolate and coating formulations; most coatings contain additional fats with individual melting characteristics, and it may be desirable to adjust the precise temperatures within the cycle to take account of the fat behavior. The seed-forming phase should be of 10–20 min duration, after which the tempered chocolate can be held until required at 34–35 °C.

9.2.2.4 Infrared Spectroscopy

Infrared spectroscopy is widely used in the food industry for the measurement of moisture, protein and fat (Cen and He 2007) in a variety of food products. Many other applications that have been reported in the literature include, for example, the rapid detection of citric and tartaric acids in orange juice (Cen et al. 2007), the evaluation of green coffee beans (Santos et al. 2012), and the analysis of changes in the secondary structure of gluten proteins due to emulsifiers (Gómez et al. 2013).

Product moisture content is important in most foods. The water molecule is a permanent electric dipole. This can be shown to explain the behavior of water as a solvent, and also its high dielectric constant. The presence of water is readily detectable, though the extent to which water molecules associate with food constituents affects their detectability. Moisture in bulk materials is seldom uniformly distributed. Any heat process, for example, sets up moisture gradients. Moisture diffusion time constants are generally longer than thermal diffusion time constants, and moisture gradients persist after the material has reached a uniform temperature. For food safety during storage, water activity is a more useful parameter than equilibrium moisture content. Microbial growth or spore germination occurs at or above the following water activity levels: *E. coli*—0.96, Salmonella—0.93, most bacteria—0.91, most yeasts—0.88, most molds—0.80, osmophilic yeast—0.62. Water activity is defined as the ratio of the partial pressure of water over the food relative to the vapor pressure of pure water at the same temperature. For closed systems at equilibrium, water activity corresponds to relative humidity, which can be measured using a wide range of low cost sensors. Drying operations readily bring moisture content down to

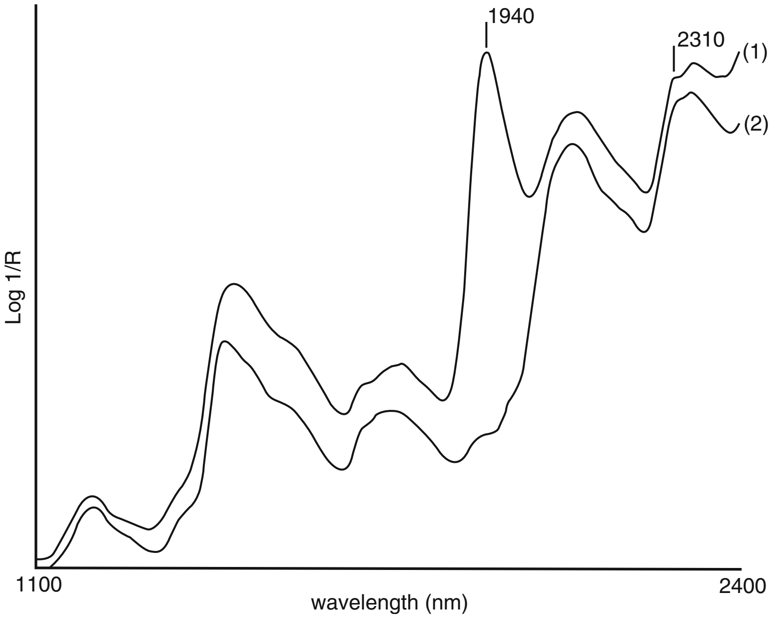


Fig. 9.2 NIR Spectra of a flour sample, (1) before and (2) after oven drying (after McFarlane 1994)

levels corresponding to 0.1 activity units, well below levels at which there is risk of spoilage. Collell et al. (2012) demonstrated that NIR spectroscopy could be employed in the nondestructive monitoring and control of the drying process in fermented sausages. Meng et al. (2012) explored the use of a method based on Fourier transform infrared (FTIR) to measure the moisture content of edible oils (refined soybean oil, olive oil, canola oil, corn oil, sunflower oil) using dry acetonitrile as the extraction solvent. They concluded that the method was amenable to automation (120 samples/h) and could be employed routinely to measure moisture in a variety of hydrophobic materials such as mineral oils, biodiesel, and fuels as well as edible oils. As such, it is in direct competition to Karl Fischer titration.

Water vapor exhibits a series of absorption bands in the microwave region due to quantization of the energy of rotation. In liquid water, these bands are broadened to such an extent that microwave energy is absorbed fairly uniformly over a wide band of frequencies. The natural vibration resonances of the water molecule occur in the infra-red part of the spectrum, and the overtones and harmonics of these lie in the near infra-red. The bands are much narrower than the microwave absorption bands of water in food materials, and the band at 1,940 nm in the near infra-red region is particularly convenient for moisture sensing. Near infra-red reflectance (NIR) is essentially a surface measurement, and its use in-line is mainly restricted to sheet materials and to processes offering a freshly exposed surface. Davies and Grant (1988) note that the predominant absorptions in the NIR spectra in foods are caused by bonds involving –OH, –NH and –CH, which correspond with the major classifications of food into carbohydrate, protein and fat. Figure 9.2 illustrates how these absorptions are distributed in a typical food product. For water content measurement, Osborne and Fearn (1986) demonstrate NIR spectra of wheat flour; they show that there is a close correlation between the difference in log (1/R) at 1,940 and 2,310 nm and flour moisture in the range 11–15 %, dry basis. NIR spectroscopy is widely used for grain moisture measurement and the methodology has been investigated in detail.

NIR analysis is used for other in-line composition measurements. Kamishikiryo et al. (1992) found absorption at 2,170 nm, due to peptide bonds, suitable for determination of protein in oil–water emulsions. Protein was determined to within 0.3 % in the range 0–10 % in the presence of 0–15 % oil. NIR can sometimes be used for measurements on bulk solid foods, if made on a freshly exposed surface. However, the most successful in-line applications of NIR have been granular or powdered materials and fluids, because representative sampling of the whole product stream can be arranged with much greater ease.

At-line NIR analyzers are used, for example, in dairy applications. In a description of the engineering of a large dairy on a greenfield site—New Zealand Dairy Group's facility in Lichfield, New Zealand—samples of cheese products are collected automatically for measurement of fat and moisture in a test which takes 20 s (Byrne 1996). The overall plant design incorporates Hazard Analysis and Critical Point Control (HACCP) principles, with mid-run Cleaning In Place (CIP) initiated and controlled by PLC. The level of automation at Lichfield is such that production of 350 tonnes/day of cheese requires only 95 employees.

As described by Wilks (1985), multiple internal reflection is used online in the simultaneous determination of Brix and dissolved carbon dioxide in carbonated beverages. The beverage flows over the surface of a cylindrical sapphire rod. Infrared radiation is focused through a chopper onto one end of the rod, and the light emerging from the other end is focused onto detectors placed behind narrow band filters. Brix was measured to better than 0.05 units, carbon dioxide to within 0.02 volumes, and monitoring of the acids in sugar-free products (the acids absorb at the same wavelength as sugar) enabled concentration of diet beverage blends to be measured to within 1 %.

An alternative form of analyzer, using ultra-violet attenuation, was supplied by Dupont for beverage analysis at Chattanooga Coca-Cola (Maczka 1989). Syrup ratio specifications set by Coca-Cola call for 100 % of a standard with a range of 100–102 %. The UV online analyzer controls the water–syrup blend to within 0.5 % for diet and sugar-containing products, and a further sensor monitors the carbonation.

Measurement of free fatty acid content (FFA) is vital in edible oil refining. Ismail et al. (1993) report the use of attenuated total reflection (ATR) with FTIR spectroscopy, to make in-line measurement of FFA. The laboratory method measures total titratable acidity, and the FTIR system mimics this, measuring carboxyl groups to within 0.02 % concentration within 2 min. The authors comment that this is an ideal application for in-line FTIR, because the oil is a single component triglyceride, which can be measured directly without dilution. Analytical methods for determining FFA in butterfat (which causes off-flavors) are labor intensive. Schooner et al. (1991) report the development of a biosensor coupled with automatic flow injection analysis, using an immobilized butyrate kinase reactor. Detection of acid at a level of 30 ppm was achieved at 15 samples/h.

9.2.2.5 Nuclear Magnetic Resonance Spectroscopy

Over the last two decades, the use of nuclear magnetic resonance (NMR) spectrometry for the characterization and analysis of foodstuffs has flourished (Spyros and Dais 2012). In a book written from the viewpoint of the food scientist, these authors address the use of different NMR techniques. They also discuss the use of magnetic resonance imaging (MRI) in food processing and assessing the natural changes in food such as ripening. Although there are numerous references in the literature to the use of NMR in food analysis in the laboratory setting, there are relatively few examples of its actual or potential use online. A selection of these is described briefly below.

Pearson et al. (1987) reported the use of a compact pulsed nuclear magnetic resonance (NMR) system for measurements on ground corn. This featured an online sampling system and automatic calibration. Bellon et al. (1992) showed that NMR is more successful than surface NIR for assessing the ripeness of some thick-skinned fruit such as cherries and grapes. Guthausen et al. (2004) described the use of a portable dedicated low-field NMR analyzer to measure the fat content in a packaged product without destruction. Two methods were described: a ratio method and a relaxation time method. The processed NMR signals were linearly correlated with fat content. This allowed single-sided NMR (Casanova et al. 2011) to be employed. In this technique, the sample is placed on the surface of the RF probe rather than in the magnet gap of the spectrometer. Haiduc et al. (2007) demonstrated the use of NMR in a truly noninvasive through-package sensor denoted the *MO*bile *U*niversal *S*urface *E*xplorer (MOUSE). This was employed to assess a microstructural quality parameter (water exudation, WE) in model systems consisting of protein-stabilized oil-in-water emulsions. The authors employed multivariate calibration techniques to establish a robust relationship between the MOUSE signals and WE. They demonstrated that the performance of the MOUSE was comparable to that of a conventional bench top NMR spectrometer and therefore showed promise for online assessment of food quality. Petrov et al. (2008) employed two single-sided NMR techniques to measure the fat and moisture contents of model samples of a cod liver oil emulsion and commercial ground beef. The authors concluded that their approach would be amenable to online analysis of food materials and as an alternative to laborious standard extraction methods employed in the laboratory.

Hills and Wright (2006) listed a number of potential online applications of NMR that could be employed in the food industry provided that suitable low-cost sensors could be developed. These included the detection of bruising, infection and physiological defects in fruit and vegetables, quality concerns related to the oil, fat and water content of processed meat, fish, dairy, egg, and cereal products, foreign body detection, and process control applications. In addition to the cost of conventional NMR equipment, the impediments at the time to the use of NMR for online sensing included the fact that the equipment was far too delicate for use in a factory environment, that the technique was too slow for monitoring product at typical conveyor speeds of 2 m/s, and that the equipment requires highly skilled and expensive operators. As a potential solution to these problems, they discussed the theory underlying the use of motional relativity in NMR and presented preliminary results obtained on an online prototype sensor. The technique eliminates the need for pulsed RF excitation and pulsed magnetic field gradients. As a result, the equipment can be built at a fraction of the cost of conventional off-line commercial spectrometers.

9.2.2.6 pH

Measurement of the pH of process fluids is usually made with a pH-sensitive glass electrode, which monitors the concentration-dependent energy change associated with the ionization of water at the gel-like hydrated surfaces of glass. A second electrode, not sensitive to pH, is required to measure the output of the glass electrode. The main problem associated with the standard sealed reference electrode was that process liquids either diffused or were thermally pumped into the electrode, thereby poisoning it. Ways to overcome this include pressurizing the electrolyte in the reference electrode, interposing an intermediate liquid between the sensitive element and the process fluid, or using a pH electrode in conjunction with a buffer solution intermediate between the electrode and the process fluid. The latter ensures a stable output even in the event of the ingress of traces of process liquor. Solid state electrodes are also available, with the sensitive electrode let into a body of sintered PTFE and potassium chloride saturated solution. These are more resistant to fouling.

9.2.2.7 Biosensors

Biosensors can be constructed by allowing an enzyme to produce ionic products from an organic species to be analyzed. Product concentration is then measurable by an ion-selective electrode. Initial applications have been for medical purposes and for environmental monitoring. Kress-Rogers et al. (1993) describe the development of a biosensor array for meat freshness measurement.

Fish and Thornhill (1988) comment on the continuing gulf between available sensors and the need for measurement of state variables in fermentation control. Some progress has been made in relating fluorescence to biomass concentration, and in developing biosensors, though few of these meet the criteria of reproducibility, stability and robustness necessary for online use. Accurate online biomass determination may become possible by measuring the dielectric permittivity of the microbial suspension.

9.2.2.8 Color

The various mechanisms causing color changes in food materials are described by Nassau (1983). The yellow and orange carotenoid coloring of carrot, corn, pumpkin, peach, and other vegetables and fruits arises from the permitted energy transitions where there are noncyclic double bonds in a chain of carbon atoms. Closely related to beta-carotene is the structure of rhodopsin, the main agent in the eye’s perception of light. Carotenoid colors are very stable to heat. The acid–base color change of anthocyanins provides the red, blue, and purple colors of beets, red cabbage, and many berries. A blue color may be produced even in an acid solution by traces of iron (hence the need for a protective inner layer in fruit juice cans). A similar reaction occurs with the closely related anthoxanin pigments, which provide the creamy white color of onion and cauliflower. The red color of meat is derived from myoglobin, and freshly cut meat quickly develops the bright red of oxygenated myoglobin on exposure to air. The browning of raw fruits and vegetables when exposed to air is the result of an enzyme-activated oxidation producing melanin. All foods char if overheated, but the browning of meats, bread, cake and fried potato is the result of the Maillard reaction between reducing sugars and amino acids. Color-measuring equipment usually describes color in terms of one of the tristimulus color scale values, and conversion between scales is easily carried out using standard formulae. Hunter and Harold (1987) identify several single number scales adopted for rating the color value of specific food materials, particularly the Yeatman scale for orange juice, and the tomato paste color index. Low et al. (2001) describe developments in the presentation and illumination of product during color sorting. Image processing, and the related technique of pattern recognition, are gradually being adopted for routine inspection tasks, and a color value is sometimes available from the image. The basic principles and practical issues associated with the measurement of color are discussed in Culver and Wrolstad (2008). Color measurements in different industry subsectors (fruit and vegetables, beverages, meats and seafood, oils, emulsions, cereals, and dairy products) are then addressed. The volume concludes with a discussion of regulatory aspects relating to the use of colorants in the USA, Europe, Central and South America, and Asia.

9.2.2.9 Chemical Contaminants, Pesticides, and Food-Borne Pathogens

A recent development in food sensor technology, the high-frequency quartz crystal microbalance (HF-QCM), has been described by Shalom et al. (2006). This technique, which has the capability of providing highly accurate real-time analysis, can be used to detect a wide range of substances in field operations, including chemical contaminants, pesticides, and food-borne pathogens such as *E. coli*, Salmonella, and Listeria. The sensor may be employed in-line or in a hand-held contamination detector. The sensor consists of an array of crystals, the surfaces of which are coated with a different material. Each of these coated surfaces selectively adsorbs a specific gaseous contaminant (or component, depending on the required application). HF-QCM is based on the piezoelectric effect. The adsorption of small traces of foreign material on the surface of a vibrating crystal increases its mass and hence decreases its resonating frequency. These changes produce a unique digital signature for each target substance, which are accurately measured within seconds using powerful pattern-recognition software.

9.3 Control Equipment

The control equipment market is dominated by a small number of multinational companies. In this section, some of the choices to be made in the selection of control actuators and operator facilities are discussed, and communication standards are reviewed.

9.3.1 Data Transmission, Computers and Programmable Logic Controllers (PLCs)

All field-mounted items associated with measurement and control require connection to a control panel. Costs are continually changing and, as in all aspects of information technology, the cost of high performance and intelligent modules tends to fall, while everywhere skilled labor costs for wiring and module installation tend to rise. These trends increasingly favor networked or distributed systems. There are other advantages of distributed systems, which make them attractive in food processing plants:

- The diversity of unit operations in food processing and the likelihood that many forms of operation are performed during any one manufacturing sequence makes it appropriate to have a local control panel for each operation, even when the area is not manned during normal production
- Distributed control allows manual control of part of the plant during, for example, process or product development
- Local control panels provide the maintenance crew with facilities which can be used without interrupting other operations
- Automated plant, particularly in areas that are staffed only intermittently, requires safety provision where there are pieces of equipment, which move by remote actuation. Interlocks and locking-off provision are more easily arranged and more securely designed if the plant controls are separate for each such area.

For plant variables measured with devices having continuous analogue ranges, signals have traditionally been transmitted either as pneumatic signals in the range 3–15 psi or as direct electrical current in the range 4–20 mA. Electrical direct-current transmission methods are popular for their immunity to impedance changes in wiring and receivers, and relative freedom from noise pick-up. Standards are well established; the ANSI/ISA standard 50.00.01-1975 defines analogue signals for electronic industrial process instruments.

Signal modulation improves the protection against interference, at the expense of more complexity. Frequency modulation, pulse width and pulse repetition rate are all used for data transmission, but of these only pulse repetition rate is widely popular, because of its convenience for digital tachometers (including the case where they are incorporated into turbine flowmeters). It has taken some years to establish agreed standards for computer-compatible data transmission. Three serial data transmission standards defined by the Electronics Industry Association (EIA) are known as RS-232C, RS-422, and RS-423. In RS-232C, the C denotes "current version," which at present is TIA 232F. Parallel data transfer is also widely used. The IEEE and IEC adopted a common international standard, IEC-60488-1 in 2004.

The electrical standards are now well accepted and adhered to, but there is still some lack of agreement on the operational control of data links, in spite of intensive efforts to harmonize "fieldbus" standards. Fieldbus is the name given to a family of industrial computer network protocols used for real-time distributed control. These have now been standardized as IEC 61158. Part of the difficulty has been that the uses of computer networks are so diverse; as a result IEC 61158 includes eight different technologies. Fieldbus Inc. (2012) provides a useful overview of the technology.

The IEEE 802.1 standard defines the relationship between other IEEE 802 conventions. IEEE 802.3 and 802.5 are the standards most used in process control. The IEEE 802.3 local area network (LAN) standard, based on Ethernet, is used for interconnection of PLCs, PCs and workstations. Industrial Ethernet operates using carrier sense multiple access with collision detection (CSMA/CD) and is compatible with the Manufacturing Automation Protocol (MAP), a standard whose origin is closely associated with General Motors and OSI. IEEE 802.5 is a token ring standard, preferred by IBM and other computer suppliers for office automation (and allowing voice as well as data communication).

Ethernet is used to link PLCs with Operator Guidance Stations at the highly integrated Almarai dairy products processing complex near Al-Kharj in Saudi Arabia (Morris 1998). Milk reception, CIP, pasteurization and other operations are governed from a central control room, with PCs used for data presentation and recording. The complex includes a wide variety of unit operations, and 26 different CIP options. Preventive maintenance software is also integrated into the overall control.

Profibus is an interconnection standard (IEC 61158/EN 50170) for field-mounted devices well supported by European manufacturers—see, e.g., Siemens (2005). An increasing number of tasks associated with system operation and maintenance are conveniently handled from a PC-style terminal, and in some applications a PC with suitable software can be linked directly to Profibus. Siemens, for example, offer a Windows Automation Center (WinAC) using Microsoft Windows NT as it is considered "future-proof" for the integration of SIMATIC and other plant-control equipment with familiar Windows software. Hardware configuration, parameter assignment, testing, commissioning and documentation can all be accomplished from the PC, together with online programming of some PLCs.

9.3.2 Plant Regulation

Every process has to have some input. Most processes have more than one recipe component, and so the performance of the process and the quality of the end product will depend to some extent on achieving the optimum blending ratio of the ingredients. Most processes also depend on the correct rate of supply of ingredients, either batchwise or continuously.

Each food process has its own set of requirements, and control packages have evolved which are suitable for particular sectors of the industry—dairies, breweries, bakeries and meat processing plants are examples of such sectors. At an automatic chocolate molding plant installed at Cadbury (since acquired by Kraft Foods), Bourneville, UK, in 1990, five workstations were provided as part of an Allen-Bradley Pyramid Integrator control package. Application software was specified by Cadbury engineers. At another Cadbury factory operated by their associated company Poulain at Blois, France, which was built in 1989, grinders and conches are controlled by 35 Telemechanique PLCs linked to a data highway; one of 30 predefined recipes is downloaded for each batch. Tempering involves 12 PID temperature control loops, and molding is performed via a digitally controlled multi-axis pouring head.

9.3.3 Operator Facilities

Operator facilities required for unit operations, for plant supervision and for the co-ordination of site activities have been reviewed by Moran (1991) with particular reference to alarm procedures. Hazardous failure modes will have been analyzed by the equipment supplier for all situations in which the supplier might be held responsible. It will be part of the conditions of supply that the integrity of safety precautions (in the form of warning devices, interlocks, and hazard condition detectors) are not compromised or invalidated during installation or in subsequent plant modification. This means that all plant is likely to be fitted with fundamental indicators to which the operator must be trained to respond. To these, the factory management will have added their preferences for combining and displaying plant condition data in such a way as to enable the process operator to optimize performance. On some plants, this optimization may be highly sophisticated, and can include cleaning cycles and maintenance scheduling.

The factory management (or system integration provider if such is employed) must work with the control-system vendor to design failure modes in such a way that the plant may operate at reduced efficiency, and shut down with minimal loss of part-processed product, if specified classes of failure should occur. This in turn means that the operator must have access to, and be trained to operate, backup facilities which remain available in the interim situation. Food-plant managers have to guard against microbiological hazards as well as observe regulations regarding electrical equipment, moving parts, and containment of hot or corrosive fluids. “Common mode” failure (such as loss of electrical supply) must not prevent an operator completing specified procedures; in most cases, it will be sufficient to provide manual actuation of critical regulators, but the microbiological aspects may demand continued data recording using secure backup power sources.

9.4 Control Strategies

Food-plant control is characterized not only by hygiene requirements but also by seasonal and other variations in most of the raw ingredients, requiring flexibility in control methods. Batch processing to a large extent reflects the scaling up of traditional manual operations. Alongside batch processing there are various forms of continuous processing, involving, for example, blending, extrusion, baking, and drying. PLCs have replaced relays and timers in almost all batch operations, but in continuous operations where analogue signals and proportional-integral-derivative (PID) feedback controllers predominate, PLCs have shared the market with dedicated loop-controlling modules. The technologies are converging, with higher range PLCs providing PID capability, and computer-based control software offering convenient sequence and timing functionality.

9.4.1 Sequence Control

The APV Computer Control System (ACCOS) was an early example of several software packages well established in food process control. Burton and Mulholland (1990) gave details of the development of the next generation of ladder logic software within APV, with reference to the safety-related software supplement issued by the UK Health and Safety Executive with their report on programmable electronic systems. The development uses the concepts of a library of sequences and a matrix of logic states. For security, the matrix is in two parts, process-related and safety-related. The library concept makes the software reusable, allowing costs of documentation and of further development to be kept to a minimum.

Batch weighing offers significantly better accuracy than continuous metering systems and, combined with the less stringent demands on reliability, this sustains the popularity of batching systems in spite of the disadvantages of greater floor space, larger number of vessels and longer and more variable standing times. Miscible fluids do not present the dispersion and segregation problems associated with mixing of powders; the main problems with dispensing fluids arise from fluid viscosity. It is hard to ensure full discharge of sticky fluid from a vessel used for batch weighing, and if volumetric dispensing is chosen rather than weighing, then entrained air becomes a common source of inaccuracy.

A straightforward example of computer-controlled batching of fluid ingredients in vessels is provided by controls for a jam and chutney plant supplied in 1990 by Practicon to Baxters of Speyside, UK. Preweighed solid and liquid ingredients are added to the cooking vessel according to a stored recipe, and visual display units and alarms prompt operators to add more fruit or pectin as required. Heating is controlled automatically to preselected temperatures, and on completion the operator is prompted to discharge the batch.

Thermal sterilization of prepackaged canned foods in retorts has been one of the most common methods for preserving food. Containers are heated in pressurized retorts for prescribed lengths of time, calculated to achieve bacterial inactivation. The heat transfer mechanism has been extensively studied in order to determine time-temperature trajectories, which guarantee inactivation without excessive overcooking. Strict regulations for the processing of canned food are laid down in most countries, and batch records must include documentary evidence of compliance. Teixeira and Tucker (1997) have reviewed the automatic control strategies which are available for food canning retorts, and they discuss approaches to process optimization based on modeling the temperature history at the coldest point (usually the center) of the can. The modeling has been extended to pouches. Teixeira and Tucker conclude that computer control of retorts provides improved utilization of resources as well as automatic preparation of formal documentation.

9.4.2 Feedforward and Feedback Control

There are numerous textbooks which describe the tuning of feedback loops; the theory includes mathematical expressions for open and closed loop response of single-input single-output systems, adaptive tuning of those loops, techniques for loops with time delays and interacting variables, and feedforward compensation for process disturbances. This theory has been summarized elsewhere (McFarlane 1994). The existence of expressions for loop tuning parameters has enabled the tuning procedures to be encoded, and they are incorporated in several of the ranges of modular controllers obtainable from various suppliers; the facility is usually referred to as “adaptive control.” Martin-Sánchez et al. (2012) reviewed various applications of optimized adaptive control methodologies, where adaptive systems theory is complemented by optimal control theory.

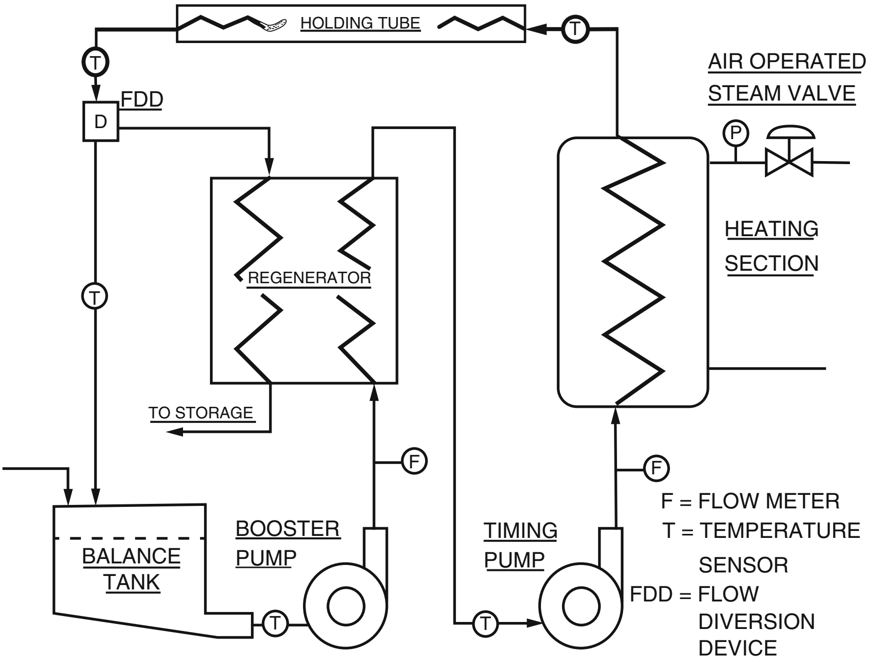


Fig. 9.3 Control of HTST treatment (after Negiz et al. 1996)

Lead/lag compensation for changes in boiler loading is one special case of feedforward control, applicable to almost any system where input disturbances can be foreseen and prepared for. If the input flowrate or temperature changes, the new steam flow requirement can be calculated and the steam valve adjusted in anticipation. It is usually an advantage to supplement feedforward or predictive control with some form of feedback; in the case of boiler control, it is beneficial to add:

- Cascade control of the steam flow, to allow for the nonlinear steam valve characteristic;
- Feedback control of final temperature, to correct any error in the model-based feedforward calculation;
- Dynamic compensation for the effect of change in the heat capacity of the exchanger.

Sunnyside Farms Dairy, Turlock, California, was opened in 1988 to produce ice cream and other products from milk from Mid Valley Dairy. A centralized computer system monitors and controls mix formulation, batch functions and pasteurization, freezing, and cleaning-in-place (CIP). Ingredient dispensing is preceded by an inventory check; each mix is sampled for milk fat and total milk solids and corrected if necessary. During pasteurization, all HTST controls are monitored and the pasteurized mix is automatically diverted if a surge tank is full or the next batch is not ready. The mix is aged at 3 °C overnight in the surge tanks. The proportion of air during freezing is calculated on the basis of feedback from the checkweigher to maintain the desired overrun, and the ratio of fruit or condiment is also maintained automatically by regulating the speed of the fruit feeder. Automation extends to storage using 1,100 captive carts, and there are three automatic order pickers.

An example of cascade and multivariable control of HTST pasteurization is given by Negiz et al. (1996), in which cascade control is used to reduce temperature fluctuations in the pasteurized product in order to reduce energy consumption. Multivariable control is used to regulate product flow rate and product temperature simultaneously, providing a potential for continuous adjustment of the product flowrate set point. A schematic of the arrangement is shown in Fig. 9.3. Not shown in the schematic is the flow diversion valve ahead of the holding tube. If lethality monitoring shows a value below a tolerance above the statutory level, flow of product back to the raw tank is triggered automatically. Tests with the system included a booster pump failure test, the result of which was a temperature fluctuation not immediately harmful to the process, but too erratic for the controllers to achieve immediate compensation. It is concluded that the cascade and multivariable control reduced fluctuations in product temperature in comparison with single-loop feedback control; however, safety concerns must be addressed before regulatory agencies can consider approval.

Milk requires pasteurization (heat treatment) for destruction of bacteria. Prolonged heating tends to denature the proteins, so short exposure to temperatures from 65 to 100 °C is preferred. This high-temperature short-time (HTST) treatment is achieved using high efficiency heat exchangers, and heat recovery (regeneration) is used to improve the thermal efficiency. In a review of the design and operation of food pasteurization processes, Hastings (1992) assesses the risks of failure of various parts of the process. In almost all installations, the heat exchanger unit is brought to its operating temperature by automatic recycling of fluid, and maintained in the desired condition once production commences by automatic stabilization of product flowrate. The conditions may be trimmed by one or more subsidiary control loops for the temperature, heat input or flowrate of the final heating and final cooling water. These subsidiary control loops are equally applicable if refrigerants other than water are used; the subsidiary loop is particularly easy to implement if the refrigerant flows in a closed circuit.

Rotary drying control has been assessed by Perez-Correa et al. (1998). A nonlinear dynamic model was specified based on mass and energy balances. The drying kinetics were derived from mass transfer principles. The performance of a three-term feedback controller for final moisture content was compared with that of adaptive control using an output predictor model. Both forms of control performed well when the dryer was subjected to normal forms of disturbance. The good performance of the adaptive controller was attributed to its capability of detecting changes in dynamic behavior. With reference to milk powder, Bloore and Boag (1982) reported the testing of mathematical models of the spray drying operation with various control configurations. They conclude that if several loop configurations appear feasible, only a study of the steady-state process input–output relationships can determine which is the most efficient. The models were useful in interpretation of regression equations describing powder quality in terms of process variables, and in testing the implications of operating practice for control of product quality.

One of the largest American producers of tomato paste, Ingomar Packaging Co, Los Banos, California, doubled its capacity in 1995 by adding a second paste evaporation/aseptic flash cooling line. In a description of the facility (Prudhomme and Bruce 1996), it is stated that the process controllers handled 600 analogue and 400 digital signals, managed from five workstations, which were redundant nodes on a Fisher-Rosemount Provox network. Another workstation in the engineering office could perform all functions, in addition to its main function of configuring the system logic. The main benefit of the new system was the elimination of process downtime; other benefits included shorter product residence times and higher throughput. The tuning of the control loops makes for smoother operation, and that in turn has given rise to significant quality improvement.

Nonlinear predictive optimal control was applied to a fruit refrigeration process by Trelea et al. (1998). The optimization criterion included economic as well as quality objectives for batch processing, where cycle duration is of the same order as settling time, so that no steady state is reached. The optimization routine approaches the optimal command profile by iteration. The algorithm was shown to be robust with respect to modeling errors as well as to measured and unmeasured disturbances.

Many interacting variables are associated with extrusion, and selection of control strategy is assisted by considering models of the process here also. Responses to processing variables can be modeled:

- As analytical results of mass and energy balances;
- By response surface methodology;
- By transfer functions.

In a review of control of twin-screw extruders, Lu et al. (1993) included four “forcing functions” as inputs—screw speed, feed rate, feed moisture and barrel temperature—and three measurable outputs—motor torque, die pressure and product temperature—in a model in which all three outputs are functions of all four inputs. Final product moisture is an output, which was not considered measurable. The review concludes that it makes sense to control the measurable process variables in closed-loop, using the available manipulated variables to adjust the process variables continuously.

Bioprocesses present a particular challenge for closed-loop control, because microorganisms are themselves adaptive to their environment. Aziz and Thomson (1996) discuss aspects of Model Reference Adaptive Control (MRAC) for which it is a requirement that all the states of the plant to be controlled are accessible. If the data contain noise, it is possible to apply filters, or alternatively the states may be estimated adaptively. Such techniques must be applied with caution, because, as with neural network and fuzzy logic calculations, it is possible for the control strategy to become unstable if the “training set” data are insufficiently representative of all possible plant conditions.

In a fermenter it is not possible to control the growth of cells directly; cells have their own in-built regulatory controls of extreme complexity. This natural control system is directed towards the preservation and continuation of life, and is capable of adapting to a changing environment, with the response depending on previous history. External controls have to be based on indirect measurement of the progress of reactions, together with monitoring of physical variables. Control strategies are usually based on some simplified model of cell behavior. To achieve the required growth rate, the respiratory quotient (RQ) is controlled at a given level by manipulating the glucose feed rate. To maintain proper respiratory conditions the dissolved oxygen tension (DOT) is controlled at a given level by manipulating the stirring rate. It was found that the DOT could be maintained at the required level of 20 % until the stirrer speed reaches maximum. The biomass increased exponentially until the oxygen level decreased at maximum stirrer speed, and linearly thereafter. Reyman (1992) concludes that application of the MRAC technique requires online sensors for biomass and glucose concentration; meanwhile, the generalized predictive control technique is feasible as a control method, which is stable, although a higher robustness may give better productivity and yeast quality.

The Kalman filter (reviewed by Brown 1991) uses noisy or fluctuating process measurements to estimate a representation of a plant in such a way as to give an assurance of stability to the resulting model. The Kalman filter is intended for use with linear systems, and bioprocess behavior is seldom linear; nonlinearity degrades the performance, but does not necessarily invalidate the approach. Brown (1991) notes that although the rate of metabolism is dependent on the pH of the culture medium, the control of pH does not in all cases assist the process. Maintenance of pH at a preset value by the addition of ammonia can be a good method of supplying an essential nutrient to a process at exactly the rate at which it is being removed by the growing culture. Most industrial bioreaction processes are aerobic and the oxygen uptake rate is another indicator of the rate of metabolism. Oxygen uptake rates are commonly measured by monitoring the outlet gas phase oxygen concentration, using a mass spectrometer or other analyzer. Additional process information can be obtained from the outlet gas carbon dioxide concentration. Robust dissolved oxygen electrodes are available for measuring the rate of growth, oxygen supply limitation and some changes in metabolism. Together these data can be used in model calculations to control aeration rates (through stirrer speed and air flow rate) and respiration rates (by limiting the supply of nutrients).

Continuous fermentation was selected for a system developed by Fluor Daniel for the Provesta subsidiary of Phillips Petroleum, installed in 1988 at Bartlesville, Oklahoma. The output from the fermenter was pasteurized and immediately spray-dried without intermediate dewatering to give up to 200 tonnes/year of varieties of protein derived from alcohols, sugars or whey permeate. The pH of the aqueous medium in the fermenter was controlled by regulating the addition of ammonia, to maintain a value in the range 3.5–4.5, dependent on the yeast strain in use. Foam in the 25,000-l fermenter vessel was induced by high-shear agitation to achieve an oxygen transfer rate close to

1 mol/l/h. 1,600 W of metabolic heat was removed by a liquid ammonia cooling system. Cell densities in excess of 120 g/l enabled the broth to be fed directly to the spray dryer, and the elimination of a dewatering stage assisted retention of mineral nutrients in the product.

In the Greenfield Implementation project by Ind Coope at Burton, UK (Banks 1989) the profile of the gravity curve was controlled by valves on the fermentation vessel cooling jackets, with additional control information being provided by a temperature probe in the vessel. The brewer can specify the gravity curve, hold the temperature by manual intervention, or advance the cycle manually to initiate cooling. Thirty-six of the 100 fermentation vessels at the site were initially included in the automation scheme. Local operator stations were linked by an Allen-Bradley Vistalan network.

A few food processes, such as the roasting of coffee beans, are exothermic, making batch reactors inherently unstable; tight temperature control is required to prevent thermal runaway. Shinskey (1992) describes a cascade control configuration for applying heating and cooling to a jacketed reactor, with a temperature control loop for the jacket separated from the temperature control for the reactor itself. Careful choice of integral and derivative functions, with protection against integral saturation, allows the control scheme to provide stable control close to the reaction temperature, and to adapt to changing reaction characteristics.

9.4.3 Statistical Process Control

Statistical process control (SPC) has received widespread attention, but it is not, in its usual form, applied automatically; operator participation is required for implementation. SPC has two main uses:

- As a guide to process operators, to prompt them to make process adjustments when specific variations in sample measurements are apparent;
- To help identify causes of variation.

The popularity of SPC is partly due to its accessibility to managers whose training does not include the engineering background necessary for an understanding of formal control theory. Miller and Balch (1990) describe the application of SPC for process improvement at the Portsmouth, Virginia, peanut butter production facility of Procter and Gamble. A primary goal was to minimize downtime for the blending/grinding operation. Process operators were asked to log the reasons for unscheduled downtime, and Pareto charts were produced, leading to modifications which reduced total downtime by 35 % and the number of stoppages by 61 %.

For a text on the use of statistical and process control in the food industry, see Hubbard (2003).

9.5 Data Management

Machine intelligence offers speed of computation, storage of detailed information, and high computational reliability; human intelligence offers pattern recognition, resourcefulness, and commonsense. The marrying of the two forms of intelligence is the key to successful plant automation.

In the design of man–machine interfaces, many devices for data input and display have been used successfully. During the 1980s, graphic screen displays and keyboards (or touchscreens) have largely displaced the former range of panel-mounted dedicated devices. Screen-based systems have obvious advantages of low cost and programmability, but it is still necessary to employ design methodology to the presentation and input of information. The opportunity to use a single screen to display many pages of information saves panel space, but brings the problem that the operator sees only a small proportion of the information available. Alarm procedures may be incorporated in the software, which places additional demands on software reliability, and on the process knowledge of those who prepare the software specification. Some independent hardwired alarm annunciation is advisable, and may be mandatory, for safe operation of a plant.

9.5.1 Operational Data

When designing a real-time automatic product inspection system, a large volume of data has to be handled in an efficient and robust procedure. Chen et al. (1998a, b) reported the use of a visible/NIR spectrophotometer system to classify poultry carcass quality at up to 91 birds/min. They used neural network analysis to reduce the number of input nodes in the application of principal component analyses (PCA), and found that 15 factors gave the best performance at maximum line speed. Some costs and estimated savings from the use of this system have subsequently been published by Watkins et al. (1999). Return on investment was estimated for a set of regimes based on the Streamlined Inspection System (SIS) for 70 birds/min formerly requiring two inspectors, and the New Line Speed Inspection System (NELS) for 91 birds/min formerly requiring three inspectors. Both lines were considered to operate on either one or two shifts. It was assumed for both SIS and NELS that, with automated inspection, there is a need for one system operator per shift plus one inspector per shift to inspect retained carcasses. The capital cost of the imaging and data processing equipment was $102,309. In the most favorable regime (NELS operating two shifts), the annualized saving was estimated to be around $55,000 and, over a 5 year period, a saving of about $2 billion might be achieved in this $6.5 billion/year industry for a capital expenditure of up to $60 million.

9.5.2 Production Records

Food quality and safety monitoring provide increasing incentives for real-time logging and display of trends in process and product measurements in all sectors of food processing. In the USA, the identification of critical control points in HACCP programs is encouraging methodical product sampling, test methods and decision criteria, which are obvious applications for real-time data processing. In the UK the “Control of Substances Hazardous to Health” (COSHH) regulations, introduced in 1990 by the UK Health and Safety Executive, impose a duty of care on food manufacturers, which is increasingly being met by installing automatic logging of process and product quality data. These further uses for plant data records will draw more staff from departments other than engineering into the teams, which specify requirements for sensors and closed-loop control.

Robotic aspects of flexible manufacturing systems are another factor likely to influence plant-wide data software policy. Robotics in food factories has so far been largely confined to assembling boxed product on pallets, and to warehouse automation. In both tasks it is incidental that the containers are for food—the same robots are used in many other industrial packing and warehouse operations. There is a food-specific robot application at a Unilever company in the UK, on a production line for a range of frozen foods. Here the incentive is to replace human operators in the unsociable environment. In this small application there are 16 motors, ten of which are part of the robot system; the other six provide simple conveying under local control. Automatic optical inspection is an integral part of the system.

An interactive online quality control system was used to link sensors installed for process control to quality control recorders at the Kilmeaden Cheese Plant, Co. Waterford, Ireland. Fitzgerald et al. (1998) show how the system increased the empowerment of the process operators by providing them with all necessary information and with decision support mechanisms. Process control systems in the factory used Ethernet to link the operational areas. HACCP, ISO 9000 and product quality recording were all part of a customized Microsoft Access database. The multiple information resource points were transparent to the user, who was presented with a single standardized and uniform environment. Significant productivity savings were claimed, together with the advantage of eliminating several intermediate stages of documentation; in turn, the need to hold and maintain identical hard-copy manuals in different parts of the plant was eliminated. Despite these improvements, the plant was closed in 2006 and production of the well-known Kilmeadan cheddar moved to Ballyragget, Kilkenny.

Reviewing the application of HACCP to seafood processing, Garrett and Hudak-Roos (1990) noted that 13 process critical control points and 23 sanitation points have been identified for cooked shrimp. For this and most other seafood operations, heat transfer to the product is more rapid than for bulkier meat products. It is required that stored seafood be thawed before processing, and a warning is required if the water temperature falls due to the presence of frozen material.

The discharge from the first stage of wrapping is often the best location on a production line for checkweighing the package, which will eventually reach the consumer. It also provides a convenient position for metal detection as a final act of quality assurance. The accuracy of dosing liquid food products is largely dependent on the precision of container manufacture, assuming that they are filled to an optically sensed level close to the neck. Other methods depend mainly on some form of weighing, though the presence or absence of product in pouches lying flat, or in trays, can be checked with optical height sensors. All countries have weights and measures legislation, and the selection of a control method depends to some extent on the rules to be applied. The conversion of UK legislation in 1979 from a minimum weight basis to the “average weight with tolerable negative error” principle stimulated the development of a range of in-line checkweighers from various suppliers. All are capable of performing running calculations of average weight and action limits according to the formulae given in the EC regulations.

9.5.3 Engineering Data

There are a large number of vendors of “supervisory control and data acquisition” (SCADA) systems, with little compatibility between them. The incompatibility is not necessarily a significant disadvantage, and numerous successful installations have been reported. When planning a system, engineering decisions are needed for the data transmission method, computer platform and software package. Most of the established vendors of process control equipment are offering personal-computer-based SCADA systems. Almost all sensor products introduced from about 1990 onwards incorporate a communications port. Software options extend as computers become ever more powerful and, with each new engineering project, it is appropriate to review software requirements. When a major incident triggers a number of alarms, the operator will have to interpret a variety of messages and he may have difficulty in concentrating on the critical indicators. If the situation reaches the stage of plant damage, failure of sensors may mean that the information presented is increasingly unreliable, adding to the difficulty of diagnosis.

Diagnostic assistance may be provided from manuals, for example in the form of the fault system matrix (FSM), constructed from “rules of thumb” (heuristics) of experienced personnel, or from process models. Embrey (1986) noted that the FSM is context-specific, and applicable only to foreseen situations; in the event of unanticipated malfunctions, operators are thrown back on their own resources. The alternative to the FSM is a set of symptom-based procedures, involving much more preparation, and designed to bring the plant to a safe, stable state from any possible excursion. Muenchhof et al. (2009) reviewed the performance of various techniques to incorporate system redundancy in fault detection and fault diagnosis.

Computer-based diagnostic assistance includes disturbance analysis systems, expert systems and influence modeling and assessment. Disturbance analysis is based on propagation of events using an engineering model. The output is more likely to be relevant for design engineers than for process operators. Expert systems are more like sophisticated versions of the FSM, capable of explaining the reasoning of the diagnosis offered but, as with FSM, expert systems are limited by the range of foreseen situations. One of the premises of the influence modeling and assessment (IMAS) approach is that the diagnostic problem confronting the operator is not lack of knowledge so much as accessing knowledge under the stress of an incident. The computer is used to simulate an operator's diagnostic thinking process and propose various causes, some of which it eliminates on the basis of absence of other indications. The program also provides comments on possible subsequent consequences of the disturbance.

9.5.4 Operator Training

The success of any new control scheme depends partly on the willingness of staff to "share" information, a requirement complicated by the trend from hierarchical to flat or network-styled responsibilities, in which authority is deliberately diffused as a way of reinforcing a feeling of common interest. Operating style has to allow a swift response to plant alerts, as well as remaining in compliance with safety regulations and policy guidelines. Occasions for decisions are more frequent in distributed than in hierarchical management, and the "opportunity windows" (period in which a decision can have a positive effect) are shorter. Sapita (1987) argues for an operations management center (OMC) to be accessible to all staff in the responsibility network facility, as opposed to putting plant data on a network. The OMC should have:

- Real-time display, and archiving, of plant and business data
- Working environment for planning, direction, and analysis of production
- Provision for engineering support.

Many control rooms fall short of this ideal, commonly in respect of documentation and media storage, work surfaces (including provision for ad hoc meetings) and agreeable ambience (comfortable seating, air conditioning, noise insulation). The functionality sought includes numerous interfaces—people–people, people–process, process–computer, and computer–people. New OMC designs should incorporate the facilities popular with operators in any existing arrangements on other plant. Those responsible for start-up and shutdown, production optimization, maintenance, and emergency procedures should all be consulted, and the individual most affected by each of these should personally approve the design.

9.6 Guide to Selection of Equipment

Processing operations can be classified into groups with similar requirements for instrumentation and control. The following tables are intended to aid selection of equipment. Categorization for this purpose leads to three distinct sets of process operations:

- Commodity processing, of large quantities of homogeneous material;
- Manufacturing of products, involving the use of recipe formulation and many specialized processing steps;
- Preserved structure products, requiring portion and packing controls, with emphasis on freshness.

Table 9.2 Categories of processing (data from Connor and Schiek (1997), for USA)

Process category sector		Value added per employee (US$/d)	Employees
Commodity processing	Corn wet milling	156.7	8,700
	Flour	87.1	13,300
	Soybean oil	97.5	7,300
	Whole milk	67.6	73,200
	Beet sugar	66.6	12,600
Manufactured products	Flavorings	259	12,000
	Breakfast cereals	245.1	16,300
	Coffee	214.5	11,400
	Prepared milk	135.7	12,000
	Cookies and crackers	89.6	46,700
	Pasta	81.6	7,700
	Cheese	60.6	31,500
	Ice cream	55.1	18,900
	Margarine and cooking oil	54.9	10,700
	Bread and cake	54.3	162,100
Products with preserved structure	Canned fruit and vegetables	65.8	67,600
	Meat processing	57.3	64,600
	Frozen fruit and vegetables	51.1	46,100
	Meat packing	47.9	122,200
	Poultry processing	42.8	12,500
	Frozen fish	29.7	36,000

9.6.1 Categories of Processing

The Institute of Food Technologists commemorated their 50th anniversary in 1988 by commissioning a survey of food processing businesses in the USA. Data from that survey is used in Table 9.2 to show that value added per employee varies widely. Using the categories identified above, food processing sectors can be classified into three groups, the first being highly automated, the second having many complex operations, and the third being labor-intensive.

In commodity processing, the number of employees is relatively small, because these operations are highly automated, and the process design has much in common with the petrochemical industry.

Manufacturing of products almost always starts with dispensing of recipes, which is an ideal application for sequence controllers (programmable logic controllers). The common preference for PLCs within food process engineering stems from this type of operation. In this group there are many other specialized operations, some with very specific control requirements.

In the last category, where portioning of fresh product takes place, there are many manual operations, and much seasonal work. These operations offer lower return on investment in automation. Table 9.2 shows that the added value per employee is low; the high numbers of employees provide an incentive to automate where possible, and rapid advances in modified atmosphere packaging to extend shelf life have, in several areas, provided the opportunity to automate entire packaging operations.

9.6.2 Control Strategies

Specialized control methods have evolved within each of the three classes of processing. Control tasks are listed in Table 9.3, together with associated control strategies.

Table 9.3 Control tasks and strategies

Application		Control task	Control strategy
Commodity processing	Corn wet milling	Continuous liquefaction	Jet cooking at 145 °C (30 s, followed by enzyme treatment)
		Saccharification	60 h at 60 °C and pH 4.5
		Isomerization	pH 7.8 to required concentration of syrup
	Oil refining	Saponification of free fatty acids	Caustic addition in proportion to FFA content of raw material
		Degumming	Centrifuge discharge pressure control
		De-odorization	Steam distillation rate
		Hydrogenation	Stirred-tank reactor with nickel catalyst, with in-line GLC for composition
	Fluid milk	Skim milk/cream separation	Stream proportions controlled from cream density
	Beet sugar	Vacuum pan concentration	Batch supersaturated, then seeded with crystals
			Conductivity, viscosity, and refractive index probes used to obtain final liquor composition
		Multiple effect evaporation	Density and product temperature control at each stage
Manufactured products	Fermentation	Increase yield	Control substrate and oxygen supply; model reference adaptive control
		Control rate	Control temperature and pressure
		Maintain uniformity	pH, agitator speed
	Extrusion	Die pressure	Screw speed, jacket temperature
		Expansion	Feedback to die pressure set point
		Work rate	Torque control, feed rate
	Continuous baking	Density	Heating profile, heat transfer rate during development
		Final moisture content	Feedback from final surface color to air temperature and/or flowrate
	Ice cream	Density	Feedback from checkweighing
		Hygiene	Automatic cleaning cycle
	Coffee	Roasting	Feedback from color change; detect onset of exothermic reaction
	Spray drying	Heat input	Fast acting inlet temperature control, with set-point cascaded from outlet temperature
	Retort	Lethality	F_0 value
		Cycle	PLC
	Combustion control	Thermal efficiency	Fuel–air ratio control
		Varying load	Feedforward control
Products with preserved structure	Shelf life extension	Irradiation	Dose monitoring
	Package atmosphere	Headspace analysis	Humidity and composition control
	Storage temperature	Air circulation	5 °C for respiring fruit and vegetables; 2 °C for meat and fish, pasta

In the first group in Table 9.3, it can be seen that the control tasks, though specialized, have features in common with other sectors of the chemical industry. Food companies can take advantage of well-developed industrial instrumentation and control techniques.

In the second group, it is the large number of highly specialized operations, which provide the main features. Equipment suppliers offer ranges of equipment tailored to food-manufacturing requirements, and the equipment is often designed with built-in sensors and controls. In these instances, food manufacturers are well advised to accept the integrated package from the equipment supplier, without demanding incorporation of control equipment of their own choosing.

Fermentation process control is a clear candidate for model-reference adaptive control; Reyman (1992) used a set of mass-balance differential equations for glucose, biomass, ethanol, dissolved oxygen and volume. The model was found to be highly nonlinear as a result of metabolic shifts affecting specific growth limits. There was also the difficulty of making estimates of state variables. Kalman filtering techniques have to be used to stabilize the estimates. Bioprocess automation remains an elusive target, well beyond the capability of the PLC technology, which has made automation reliable and effective in other food operations.

In a few cases, in extrusion operations for example, ingredient streams have to be continuously blended in accurate proportions. This is a much more demanding control requirement, because there has to be provision for regular calibration of flow-measuring equipment. If it is possible to verify the overall consumption periodically, for example by measuring loss-in-weight from a supply vessel, then the calibration of the flowmeters can be updated without interrupting the flow. Another technique is to use a by-pass to divert the flow while the flowmeter is recalibrated.

A further check on the accuracy of recipe control is to use a supervisory monitoring system to continually recalculate material balances. This may need to include allowance for moisture content of ingredients or finished product. Moisture content is difficult, and sometimes impossible, to measure in-line with sufficient accuracy, so the supervisory system may need provision for the subsequent input of analytical data from the laboratory.

The diversity of processes for the heat treatment of food leads to a correspondingly wide range of methods for process control. All heat processes involve time constants associated with diffusion rates, and control strategies usually include feedback via proportional-integral-derivative (PID) controllers. Feedforward control is also useful where changes in the heat load on the process are predictable, and valuable improvement in control system response can often be achieved by cascade control. Here, the output from a feedback loop with a long time constant is used to alter the set point of a fast-acting inner loop. For example, in the steam injection method for ultra-high-temperature (UHT) treatment of milk, feedback control of peak temperature is improved if the flowrate is held constant by a fast-acting control loop for flow of product through the heat exchanger.

In the last group, integration of control equipment is almost universal in the supply of automated packaging equipment, and food manufacturers have little reason to make choices of sensing and control hardware, except in the case of stand-alone units such as checkweighers and metal detectors.

9.6.3 Unit Operations

Process variables all need to be controlled at each separate stage of food manufacture. Sensors for process conditions were outlined in Sect. 9.2.1. A few examples of particular process variables and the preferred means of measurement are shown in Table 9.4. There are large numbers of other basic measurements, which are sufficiently routine that individual selection can be left to the process equipment supplier.

A large variety of processes are used for cooking and sterilizing food items. In almost all cases, thermocouples are convenient and cost-effective for measurement of process temperature, but this is not the same as the temperature within the product. Temperatures and temperature gradients within the product are difficult and sometimes impossible to measure directly. It is generally regarded as

Table 9.4 Examples of process sensors for unit operations

Process variable	Type of sensor	Application
Air temperature	Thermocouple	Heat processes
Flow rate	Turbine meter	HTST
Lethality	Time–temperature	Retort
Pressure	Differential pressure cell	Contents gauging
Steam flow rate	Orifice plate	Evaporators
Level	Differential pressure cell	Contents gauging
Flow rate	Magnetic flowmeter	Ohmic heating
Power	Wattmeter	Extrusion cooking
Power	Wattmeter	Reactor stirrer
Pressure	Strain gauge	Extrusion cooking
Jacket temperature	Thermocouple	Extrusion cooking
Throughput	Belt weigher	Continuous mixing
Air velocity	Hot wire anemometer	Baking oven
Heat input	Heat flux	Baking
Oven humidity	Dew point sensor	Baking
Level	Ultrasonic reflection	Contents gauging

safe to estimate internal temperatures using well-tried models of thermal behavior, which include heat-flux coefficients.

9.6.4 Automated Quality Assessment

There are incentives for productivity improvement in quality assurance as in all other departments, and quality checks that are labor intensive can in some cases be automated. In a few of these, the analyzer can be installed in-line with automatic sampling but, in many more cases, product samples are collected manually for automated measurement under laboratory conditions. Most of the analyzers shown in Table 9.5 can be installed in-line. They are consequently capable of generating data, which could be used in closed-loop feedback control. Few such loops have been implemented, but there is much scope for future development.

9.7 Conclusions

Control and monitoring of food-manufacturing processes involves measurement of process conditions and product attributes using many different forms of sensing. Most have been automated, and many are routinely carried out online. There is little or no opportunity to inspect all of the product, so some degree of sampling is necessary. Care must always be taken to ensure that sampling is representative.

Control hardware and control strategies likewise employ widely varying design procedures and application methods. Consolidation of control equipment suppliers has occurred, and progress has been made in establishing open standards for data communication between devices from different manufacturers. These communication methods have recently become sufficiently reliable and robust to permit control equipment from more than one vendor to be linked to a common data network in the production area. This presents users with a wider choice of suppliers of control hardware and software, and the responsibilities of the system integrator (who may employed by the user, or an equipment supplier, or an independent consultancy) are correspondingly more complex.

Table 9.5 Analyzers for product quality

Quality parameter	Analyzer	Sectors for application
Dissolved gas	Infra red transmission	Dissolved in beverages
Caffeine content	Chromatograph	Decaffeination
Bulk moisture	Infra-red reflectance	Powders and granules
Bulk moisture	Total internal IR reflection	Butter; yellow fat spreads
Suspended solids concentration	Ultrasonic absorption, or light scattering	Fruit juices
Solid fat content	Pulsed NMR	Confectionery
Crystalline form	Differential scanning calorimeter	Confectionery
Degree of bake (Maillard reaction)	Colorimeter	Bread, cake, cookies, and crackers
Dissolved sugar content	Refractive index	Beverages
Water activity	Relative humidity	Filling; enrobing
Protein	NIR	Flour milling
Particle size	Laser light scattering	Chocolate refining
Vitamin content	Liquid chromatography	Oils and fats
Headspace analysis	Gas chromatography	Modified atmosphere packaging
Trace elements	Atomic absorption spectrometry	Cocoa; coffee; nuts
Fat content	Densitometer	Milk standardization
Syrup concentration	UV attenuation	Fluid blending
Free fatty acid content	Fourier transform IR spectrometry	Oil refining
pH	Glass electrode	Jam; cheesemaking

Developments continue in all sectors of control engineering, driven partly by pressures to be ever more rigorous in hygiene practice, partly by economic incentives for increased plant yield and efficiency, and partly by the unrelenting pace of development in information technology.

The capital cost of control equipment is only part of the cost of adopting automatic control. A study undertaken by Honeywell during 1990 covered ten fine chemical companies, which had had Honeywell systems for 8 years or more, and had individuals with knowledge about lifecycle costs and automation benefits (Conroy 1992). Lifecycle costs were divided into categories of:

- Distributed control system hardware and software;
- System maintenance, spares, and service contracts;
- Internal and external training, including travel;
- Engineering labor costs.

Spreading the cost of the first item, the system itself, over a 10-year nominal lifetime, Conroy found that the users' cumulative spending on system maintenance was 16 % of the system cost, on training 20 %, and on engineering labor 116 %. This gave a total "lifetime" support cost averaging 152 % of system cost. Conroy commented that the system maintenance cost is exceptionally low for Honeywell distributed control systems, with users reporting four times higher maintenance costs for earlier systems that had been replaced. Modern systems from other suppliers offer similar reliability, which is reflected in lower contract maintenance charges.

Lateness, cost overruns and downgrading of target performance occur in food-engineering projects, as in other real time computer applications. Software defects are most frequently cited as the cause, and the cost of rectifying defects is likely to be a significant proportion of commissioning costs. Realistic and methodical system specification is very worthwhile.

Control system design for a large site is a major undertaking, requiring long lead times. Food-manufacturing operations are technically complex, frequently labor- and energy-intensive, and prone to generate waste product. They are dispersed among innumerable sites around the world, most of them with only rudimentary engineering support. Control tasks described in this chapter have been illustrated mostly by reference to large-scale manufacturing operations, where marginal improvements in performance are worth large sums of money, and sufficient to justify man-years of applications engineering.

References

Aziz, K.I. and Thomson, M. (1996) “Output driven minimal controller synthesis with an adaptive observer”, Proc. I. Mech. E., Part I, 210, 131–139.

Banks, D. (1989) “Fermentation profiles monitored”, Control Systems, 6(2), 30–31.

Bellon, V., Cho, S.I., Krutz G.W. and Davenal, A. (1992) “NMR ripeness sensor”, Food Control, 3(1), 45–48.

Bloore, C.G. and Boag, I.F. (1982) “Simulation study of a spray dryer”, New Zealand J. Dairy Sci. and Technol., 17, 121–134.

Bourne, M.C. (2002) “Food texture and viscosity”, 2nd edit., Academic Press, New York.

Brown, D.E. (1991) “Bioprocess measurement and control”, Chem. and Ind., Sep., 678–681.

Burton, C.M. and Mulholland, S.P. (1990) “Ladder logic software for flexible process control”, Food Control, 1(2), 98–104.

Byrne, M. (1996) “Plant of the year: The big cheese”, Food Eng. Int., 21(4), 39–51.

Casanova, F., Perlo, J. and Blümich, B. (2011) (eds), “Single-sided NMR”, Springer-Verlag, Berlin.

Cen, H. and He, Y. (2007) “Theory and application of near infrared reflectance spectroscopy in determination of food quality”, Trends in Food Sci. and Technol., 18, 72–83.

Cen, H., Bao, Y., He, Y. and Sun, D-W. (2007) “Visible and near infrared spectroscopy for rapid detection of citric and tartaric acids in orange juice”, J. Food Eng., 82, 253–260.

Chen, Y.R., Park B., Huffman R.W. and Nguyen M. (1998a) “Classification of on-line poultry carcasses with backpropagation neural networks”, J. Food Proc. Eng., 21, 33–48.

Chen Y.R., Nguyen M. and Park B. (1998b) “Neural network with principal component analysis for poultry carcass classification”, J. Food Proc Eng., 21, 351–367.

Collell, C., Gou, P., Arnau, J., Munõz, I. and Comaposada, J. (2012) “NIR technology for on-line determination of superficial aw and moisture content during the drying process of fermented sausages”, Food Chem., 135, 1750–1755.

Connor, J.M. and Schiek, W.A. (1997) “Food processing: an industrial powerhouse in transition”, 2nd edit., John Wiley & Sons, New York.

Conroy, R.C. (1992) “Control system costs”, Control Systems, Feb, 29–30.

Culver, C.A. and Wrolstad, R.E. (2008) “Color quality of fresh and processed foods”, ACS Symposium Series, Volume 983, American Chemical Society, Washington, DC.

Davies, A.M.C. and Grant A. (1988) “Near infrared spectroscopy for the analysis of specific molecules in food” in Crease, C.S., Davies A.M.C. (eds) “Analytical applications of spectroscopy”, Royal Society of Chemistry, London. pp. 46–90.

Embrey, D.E. (1986) “Training operators for abnormal situations”, Chem. and Ind., No.13, 454–459.

Fieldbus Inc. (2012) “IEC 61158 technology comparison: State of the bus”, Fieldbus Inc., Austin TX. http://www.fieldbusinc.com/downloads/fieldbus_comparison.pdf.

Fish N. and Thornhill, N. (1988) “Monitoring and control of fermentation”, Chem. Engr., Sept, 31–33.

Fitzgerald, N., McGrath, M.J., O’Connor, J.F. and Phelan, N. (1998) “Integration of on-line quality control into the process control environment for cheese manufacturing”, Food Control, 9(6), 369–377.

Garrett, E.S. and Hudak-Roos, M. (1990) “HACCP for seafood”, Food Technol., 44(5), 159–165.

Gómez, A.V., Ferrer, E.G., Añón, M.C. and Puppo, M.C. (2013) “Changes in secondary structure of gluten proteins due to emulsifiers”, J. Molecular Structure, 1033, 51–58.

Guthausen, A., Guthausen, G., Kamlowski, A., Todt, H. and Burk, W. (2004) “Measurement of fat content of food with single-sided NMR”, J. Amer. Oil Chemists’ Soc., 81(8), 727–731.

Haiduc, A.M., Trezza, E.E., van Dusschoten, D., Reszka, A.A. and van Duynhoven, J.P.M. (2007) “Non-invasive ‘through-package’ assessment of the microstructural quality of a model food emulsion by the NMR MOUSE”, LWT – Food Sci. and Technol., 40, 737–743.

Hastings, A.P.M. (1992) “Design, operation and control of food pasteurization processes”, Food Control, 3(1), 27–32.

Hills, B.P., Wright, K.M. (2006) “Motional relativity and industrial NMR sensors”, J. Magnetic Resonance, 178, 193–205.

Hubbard, M.R. (2003) “Statistical quality control for the food industry”, Kluwer Academic/Plenum, New York.

Hunter, R.S. and Harold, R.W. (1987) “The measurement of appearance”, 2nd edit., Wiley-Interscience, New York.

Ismail, A.A., van der Voort, F.R., Emo, G. and Sedman, J. (1993) “Measurement of FFAs by FTIR”, J. Amer. Oil Chem. Soc., 70(4), 335–341.

Kamishikiryo, H., Hasegawa, K., Takamura, H. and Matoba, T. (1992) “NIR measurement of protein”, J. Food Sci., 57(5) 1239–41.

Kress-Rogers, E. and Brimelow, C.J.B. (eds) (2001) “Instrumentation and sensors for the food industry”, 2nd edit., Woodhead, Cambridge.

Kress-Rogers, E., D’Costa, E.J., Sollars, J.E., Gibbs, P.A. and Turner, A.P.F. (1993) “Measurement of meat freshness in situ with a biosensor array”, Food Control, 4(3), 149–154.

Low, J.M., Maughan, W.S., Bee, S.C. and Honeywood, M.J. (2001) “Sorting by colour in the food industry”. in Kress-Rogers, E. B. and Brimelow, C.J.B. (eds) “Instrumentation and sensors for the food industry”, 2nd edit, Woodhead, Cambridge.

Lu, Q., Mulvaney, S.J., Hsieh, F. and Huff, H.E. (1993) “Control of a twin-screw extruder”, Food Control 4(1), 25–33.

McFarlane, I. (1994) “Appendix: Control theory” in “Automatic control of food manufacturing processes”, 2nd edit., Blackie Academic & Professional, Glasgow.

Maczka, P.E. (1989) “On-line analysis at Coca-Cola”, Instrum. Technol., 36(1), 37–39.

Martin-Sánchez , J.M., Lemos, J.M. and Rodellar, J. (2012) “Survey of industrial optimized adaptive control”. Int. J. of Adaptive Control and Signal Processing (Special issue: Industrial optimized adaptive control), 26(10), 881–918.

Meng, X., Sedman, J., and van de Voort, F.R. (2012) “Improving the determination of moisture in edible oils by FTIR spectroscopy using acetonitrile extraction”, Food Chem., 135, 722–729.

Medlock, R.S. and Furness, R.A. (1990) “Mass flow measurement review”, Measurement and Control, 23(4), 100–113.

Miller, T. and Balch B. (1990) “SPC in food processing”, Instrum. Technol., 37(7), 32–34.

Moran, H. (1991) in Moore, C.A. (ed.) “Automation in the food industry”, Blackie Academic & Professional, Glasgow.

Morris, C.E. (1998) “Almarai: World class dairy in the desert”, Food Eng. Int., 23(3), 31–38.

Muenchhof, M., Beck M. and Isermann R. (2009) “Fault-tolerant actuators and drives - Structures, fault detection principles and applications”. Annual Reviews in Control 33(2), 136–148.

Nassau, K. (1983) “The physics and chemistry of color”, Wiley-Interscience, New York.

Negiz, A., Cinar, A., Schlesser, J.E., Ramanauskas, P., Armstrong, D.J., and Stroup,W. (1996) “Automated control of high temperature short time pasteurization”, Food Control 7(6), 309–315.

Norton, I.T., Spyropoulos, F. and Cox, P. (2011) (eds) “Practical food rheology. An interpretive approach”, Wiley-Blackwell, Chitchester, UK.

Osborne, B.G. and Fearn, T. (1986) “Near infra-red spectroscopy in food analysis”, Longman, Harlow/Wiley, New York.

Patel, P.D. and Beveridge, C. (2003) “In-line sensors for food analysis”, Chapter 12 in Lees, M. (ed.) “Food authenticity and traceability”, Woodhead, Cambridge.

Pearson, R.M., Ream, L.R., Job, C. and Adams J. (1987) “Use of NMR spectrometers for process control” Cereal Foods World, 32(11), 822–826.

Petrov, O.V., Hay, J., Mastikhin, I.V. and Balcom, B.J. (2008) “Fat and moisture content determination with unilateral NMR”, Food Research International, 41, 758–764.

Perez-Correa, J.R., Cubillos, F., Zavala, E., Shene, C. and Alvarez, P.I. (1998) “Dynamic simulation and control of direct rotary dryers”, Food Control, 9(4), 195–203.

Prudhomme, R. and Bruce, D. (1996) “Tomato paste packer improves productivity”, Instrum. Technol., 43(8), 32–36.

Rao, M.A. (2007) “Rheology of fluid and semisolid foods: Principles and applications”, Springer, New York.

Reyman, G. (1992) “Modelling and control of fed batch fermentation of bakers yeast”, Food Control 3(1), 33–44.

Santos, J.R., Sarraguc¸ M.C., Rangel, A.O.S.S. and Lopes, J.A. (2012) “Evaluation of green coffee beans quality using infrared spectroscopy: A quantitative approach”, Food Chem., 135, 1828–1835.

Sapita, R.F. (1987) “Operation management centre specification”, Process Eng., 68(7), 55–59.

Schooner, F., Simard, R.E. and Pandian, S. (1991) “Test for FFA in butter using immobilised enzyme”, J. Food Sci. 56(5) 1229–32.

Shalom, D., Dayan, L., Shanzer, A., Shatzmiller, S. and Schwimmer, A. (2006), “Nanotechnology detection sensors for food quality and safety control”, http://www.foodsafetymagazine.com/article.asp?id.

Shinskey, F.G. (1992) “Control of temperature in batch reactors”, Instrum. Technol. 39(4), 69–72.

Siemens (2005) “Profibus according to IEC 61158/EN 50170”, Siemens Aktiengesellschaft, Munich, Germany.

Smolander, M., Alakomi, H.-L., Ritvanen, T. and Vainionpää, J., Ahvenainen, R. (2004) “Monitoring of the quality of modified atmosphere packaged broiler chicken cuts stored in different temperature conditions. A. Time-temperature indicators as quality-indicating tools”, Food Control, 15, 217–229.

Spyros, A. and Dais, P. (2012) “NMR spectroscopy in food analysis”, RSC Publishing, Royal Society of Chemistry, London.

Talbot, G. (2009) “Chocolate temper”, Chap. 12 in. “Industrial chocolate manufacture and use”, 4th edit, (ed.) Beckett, S.T., Blackwell, Oxford.

Taoukis, P.S., Fu, B. and Labuza T.P. (1991) “Time-temperature indicators”, Food Technol. 45(10), 70–82.

Teixeira, A.A. and Tucker, G.S. (1997) “On-line retort control in thermal sterilisation of canned foods”, Food Control, 8(1), 13–20.

Tothill, I. (2003) “Rapid and on-line instrumentation for food quality assurance”, Woodhead, Cambridge.

Trelea, I-C., Alvarez G. and Trystram G. (1998) “Nonlinear predictive optimal control of a batch refrigeration process”, J. Food Process Eng., 21(1), 1–32.

Watkins, B., Lu, Y.C. and Chen Y.R. (1999) "Economic value and cost of automated on-line poultry inspection for the US broiler industry", Food Control 10(2), 69–80.

Wedd, M. (1993) "Particle sizing", in "Food process monitoring systems", Pinder, A.C. and Godfrey, G., (eds), Blackie Academic & Professional, Glasgow, pp. 102–128.

Wikipedia (2012a) "Coriolis effect", http://en.wikipedia.org/wiki/Coriolis_effect, last updated 22 September.

Wikipedia (2012b) "Mass flow meter", http://en.wikipedia.org/wiki/Mass_flow_meter, last updated 29 August.

Wilks, P. (1985) "On-line monitoring system for beverages", Amer. Laboratory, Dec, 76–78.

Wren, J. (1985) "Sensing and process control in tomorrow's food and drink industry", FDF Working Party Report, London.

Zhou, W. and Therdthai, N. (2012) "Instrumentation, sensor design and selection", Chapter 8 in "Handbook of Food Process Design, Volume 1", Ahmed, J. and Rahman, M.S (eds), John Wiley & Sons, Chitchester, UK.

Chapter 10
Use of Computers in the Design of Food-Manufacturing Facilities

D. Hartono, G. Joglekar, and M. Okos

10.1 Introduction

Although computers have been used for many years in the design of food manufacturing facilities, recent advances have allowed the design process to be even more efficient. Process design, which encompasses a broad array of activities, is based on unit operations, transport phenomena, reaction engineering, process control, and process economics. This approach has been successfully applied to the design and operation of large processing plants, handling mostly homogeneous materials, where the required physical properties data are available or can be predicted using reliable techniques. More recently, it has been extended to heterogeneous, formulated materials in continuous, batch, and flexible processes. Computer-aided process design uses process modeling extensively. Modeling is defined as the procedure used to translate the physical laws describing a process into mathematical equations in order to analyze or design the process. Simulation software is used to predict the real performance of a process and is based on mathematical modeling plus an appropriate graphical user interface in a computer environment. Design is a procedure for sizing and rating a process in order to achieve a specific goal, such as economic production, product quality, and protection of the environment. Table 10.1 summarizes the basic definitions (Maroulis and Saravacos 2003).

Computer-aided process design is often driven by the increasing demand to produce the highest quality of product in the shortest amount of time, and also the need to reduce cost. Traditionally, design engineers and scientists have approached the problem by constructing a physical prototype and then testing it. However, this approach is very expensive and time consuming. Additionally, the prototype is difficult to modify, since it goes through irreversible changes during testing. Engineers have used simplified physical models and handbook calculations to reduce the need for building physical prototypes (Datta 1998). While this approach is quick and inexpensive, the results are however imprecise because of the many simplifying assumptions made.

Computer prototyping allows the engineer to build a model of the plant that is as close to the physical model as possible. An accurate model, which involves solving the set of partial differential equations that exactly describe the physics of the model, will work just like a physical model. It is

---

D. Hartono • M. Okos (✉)
Department of Agricultural and Biological Engineering, Purdue University, 225 South University Street,
West Lafayette, IN 47907, USA
e-mail: okos@purdue.edu

G. Joglekar
School of Chemical Engineering, Purdue University, 480 Stadium Mall Drive, West Lafayette, IN 47907, USA
e-mail: gjogleka@purdue.edu

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_10,

Table 10.1 Basic definitions

Modeling: is the procedure to translate the physical laws of a process into mathematical equations
Simulation: is the appropriate software which "guesses" the real performance of a process
Design: is a procedure to size and rate a process in order to obtain a specific goal
Size: Given the process specifications, calculate the equipment size and characteristics
Rate: Given the process specifications and equipment size and characteristics, calculate the operating conditions

known that computer software is an essential tool for food process engineers. Its capabilities provide a fast calculation, large storage, and logical decisions, permits engineers solve larger problems and to do it much more rapidly than before. With the information made available, the emphasis can therefore shift from problem solving to planning, conceiving, and interpreting. Process design is one of the engineering functions that have been impacted by computers (Peters et al. 2003).

The use of a computer has several advantages in a food product and process development environment (Datta 1998):

- It provides an inexpensive and quick testing of "what-if" scenarios. This can shorten the design cycle, reduce costs, increase profits, and reduce process development time (Petrides 1994).
- It provides insight into complex processes that otherwise would be difficult to understand.
- It allows front-end engineering that makes prototypes closer to the optimum.
- It makes concurrent design and analysis possible. While the experiment is underway, results can be simultaneously used to further optimize the process, which will reduce the amount of experiments.
- When used with sound engineering judgment, it can efficiently aid an engineer in generating high quality designs with lower capital and production costs and improve safety and reliability (Winter 1992).
- The use of a single or set of computer software packages can improve communication between process development groups working on the same project (Petrides 1994)

These advantages have been realized in a significant way mainly in the chemical process industries. However, the use of computational software is rapidly increasing in the food processing industries. Computer prototyping uses several terms, for example computer-aided engineering (CAE) and simulation-based engineering. Computer prototyping uses computers to build and test the models of products and processes to reduce the number of physical prototypes that might be needed. Computer-aided design (CAD) has the same goals as CAE but is limited to only geometric manipulations without taking into account any physics of the process. CAE can include computational mechanics to solve rheological and stress-related problems, computational fluid dynamics (CFD) and heat transfer to solve flow, heating, and cooling problems, and process simulation software.

10.2 Equipment and Process Simulation Software

10.2.1 Introduction

Recently, there has been much activity in applying computer-aided techniques in process design, which is the major component of computer-aided process engineering (CAPE). CAPE receives considerable attention at the annual European Symposium on Computer-Aided Process Engineering (ESCAPE), the Proceedings of which are published in the journal *Computers and Chemical Engineering* (Saravacos and Kostaropoulos 2002).

The main emphasis of computer-aided process engineering has been on the modeling, simulation, and optimization of process systems, specifically on flowsheet development, separation processes, and energy utilization. The processing of gases and liquids has received much attention due to the

Table 10.2 Classification of unit operations employed in food processing

Group of operations	Typical food processing operations
Mechanical transport	Pumping of fluids Pneumatic conveying Hydraulic conveying Mechanical conveying
Mechanical processing	Peeling, cutting, slicing Size reduction Sorting, grading Mixing, emulsification Agglomeration Extrusion, forming
Mechanical separations	Screening Cleaning, washing Filtration Mechanical expression Centrifugation
Heat transfer operations	Heating, blanching Cooking, frying Pasteurization Sterilization Evaporation Cooling, freezing, thawing
Mass transfer operations	Drying Extraction, distillation Absorption, adsorption Crystallization from solution Ion exchange
Membrane separations	Ultrafiltration Reverse osmosis
Nonthermal preservation	Irradiation High pressure Pulsed electric fields
Packaging	Filling, closing Metallic, plastic packages Aseptic packaging

availability of reliable prediction methods and databanks of physical, thermodynamic, and transport properties for these materials. In contrast, in the past, limited attention has been given to the processing of solids and semisolids, due to difficulties in modeling and to insufficient data on their engineering properties (Peters et al. 2003). However, the more recent developments in process design are directly applicable to food process design and emphasize the quality and safety of the processed food products (Maroulis and Saravacos 2003).

10.2.2 Unit Operations in Food Processing

The physical operations involved in food processing can be analyzed by applying the established chemical engineering concepts of unit operations and transport phenomena (Fryer et al. 1997). These concepts have been successfully adapted to food processing, taking into consideration the complexity of food materials and their sensitivity to processing conditions (Valentas et al. 1997). Generalized models of unit operations were analyzed by Diefes et al. (2000). The unit operations of food processing are classified on the basis of the processing equipment, with typical examples being shown in Table 10.2 (Saravacos and Kostaropoulos 2002). Mechanical processing operations constitute a very important part of food processing, dealing mostly with solid and semisolid materials. Size reduction, agglomeration, mixing, and extrusion, developed in the chemical process industries, are adapted and applied to various food processes. Sorting, grading, peeling, slicing, expression, and forming require specialized equipment, which has been developed for various food products and processes (Saravacos and Kostaropoulos 2002).

10.3 Flowsheeting Software

Steady-state flowsheeting programs have been under development since the late 1950s (Peters et al. 2003). The first applications were found in performing mass and energy balances on chemical processes. Today, flowsheeting and process design software for chemical processing applications is very sophisticated. Similar computer-aided process design software has been slow to emerge for food and bio-processing applications.

In food process design, flowsheets similar to those of chemical process design are used, i.e., the process block diagram (PBD), process flow diagram (PFD), process control diagram (PCD), and process instrumentation and piping diagram (PID) (Saravacos and Kostaropoulos 2002).

The selection of a process flowsheet in the chemical and petrochemical industries requires extensive computer calculations and simulations, due to the large number of possible process configurations. On the other hand, the selection of most food process flowsheets is confined to a limited number of alternatives, due to well-defined basic processing operations, for example, sterilization, evaporation, drying, or packaging (Saravacos and Kostaropoulos 2002). Equipment such as heat exchangers can increase the number of alternatives, for example, for energy optimization, in parts of the basic flowsheet. Food processes handling liquid foods, such as milk and vegetable oils, require more complex flowsheets.

Two dimensional (2D) flowsheets are mainly used for various process equipment and plant representations. In special cases, three-dimensional (3D) diagrams offer a better visualization of complex equipment or plant (ChE 1999).

Process block diagrams (PBDs) are widely used for simple representation of the process, and for preliminary calculations of the material and energy balances. Each rectangular block represents an individual unit operation or group of operations. The process flow diagrams (PFDs) or process flowsheets show more details of the process or plant, using specific symbols for equipment, piping, and utilities.

Both PBDs and PFDs can show process details, such as material flowrates (kg/h), energy flows (kW), temperatures (°C), and pressures (bar), and they can be combined with tables of data. The process control diagrams (PCDs) show the position of the control units in the processing lines, and their connection to the sensors. The process instrumentation and piping diagrams (PIDs) indicate the type and location of instrumentation and the type and connections of pipes. In addition to PBDs and PFDs, layout diagrams, showing the position of the processing equipment in the food plant are used.

A block diagram, a process flowsheet, and a layout diagram for the same food processing plant are illustrated in Figs. 10.1–10.3. The plant chosen is a tomato-processing facility, producing tomato paste, involving several unit operations and processes and a variety of processing equipment. Figure 10.4 shows a 3D flowsheet for the same plant, which provides a better visualization of the layout of the equipment (Saravacos and Kostaropoulos 2002).

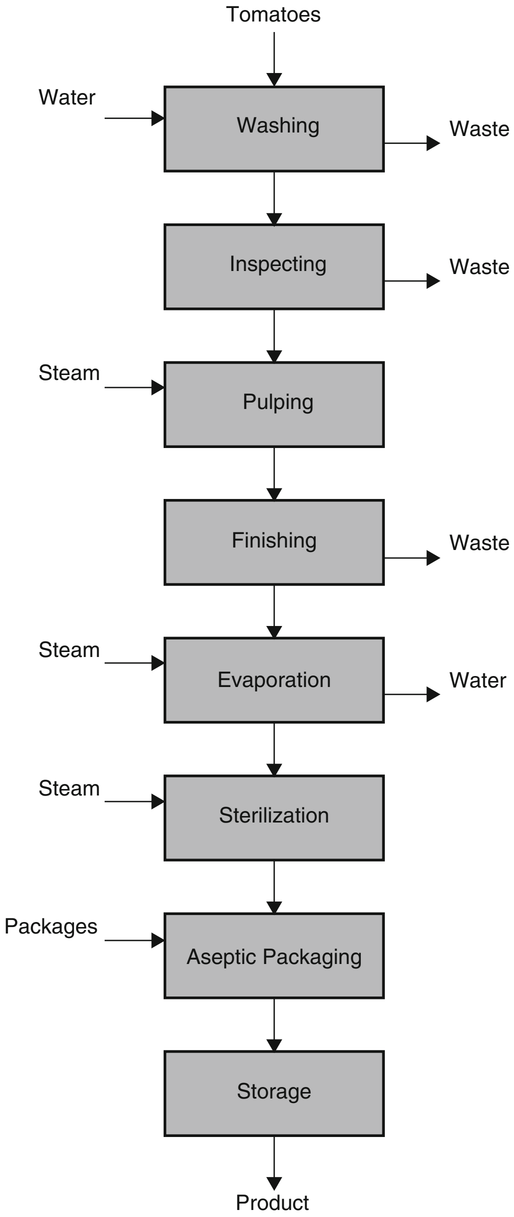


Fig. 10.1 Simplified process block diagram for tomato-paste-processing plant

10.4 Selected Software Packages

10.4.1 Introduction

A number of integrated process flowsheeting packages are either commercially or academically available for chemical and petroleum applications (Table 10.3). Among these software packages, *ASPEN PLUS* is perhaps the most widely used in both industry and academia. However, like most chemical process design software, it cannot be easily used for food or bio-process design applications

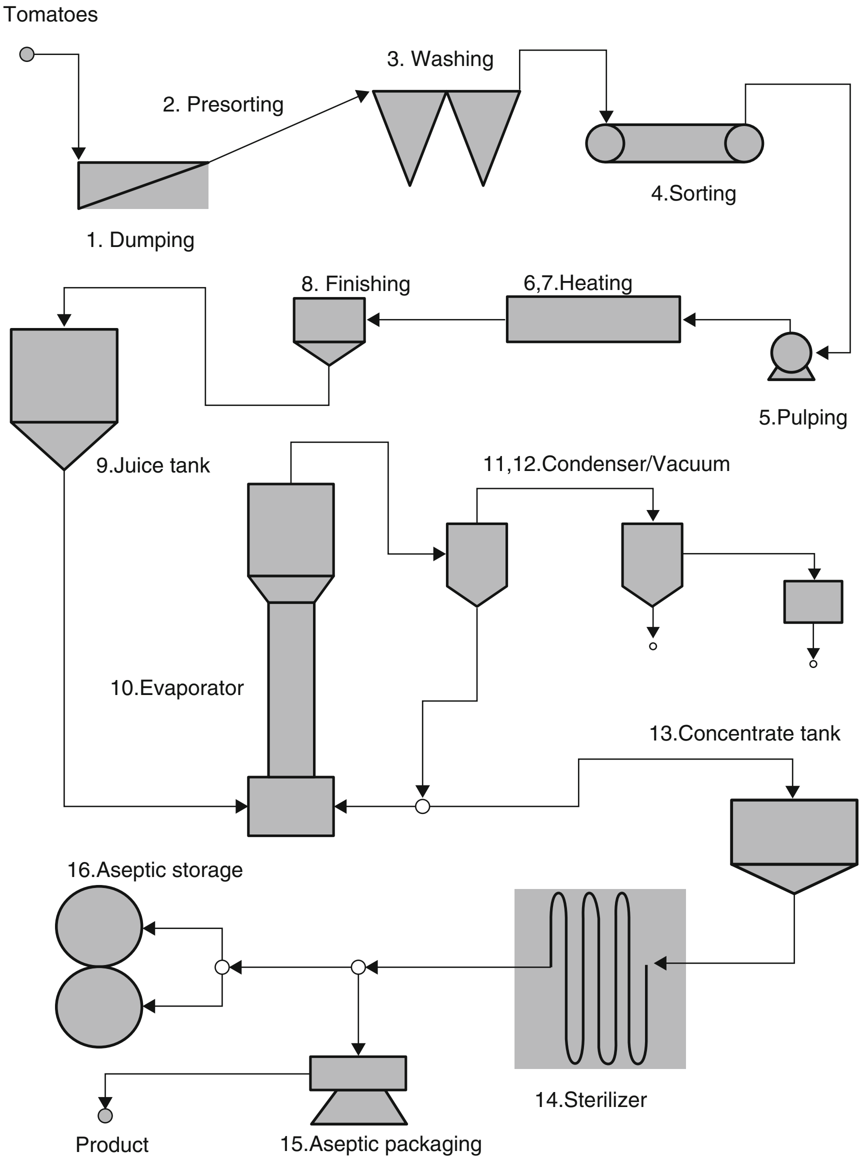


Fig. 10.2 Simplified process flow diagram for tomato-paste-processing plant

because streams must be represented as mixtures of quantifiable known chemicals. Moreover, there are considerable difficulties associated in modeling solids.

While the chemical specification of streams makes *ASPEN PLUS* useful in the design of processes such as refining vegetable oil (Chakroun et al. 1995), it is typically not possible to specify food streams in this manner. Since many of the thermo-physical property models depend on the chemical specification of the streams, the food engineer must make gross assumptions. Also, the level of sophistication and the terminology used by these programs is generally unfamiliar to the food scientist and to inexperienced food and bio-process engineers.

It is important to note that chemical engineering systems research continues to drive the development of flowsheeting and steady-state computer-aided process design (CAPD) software. The high

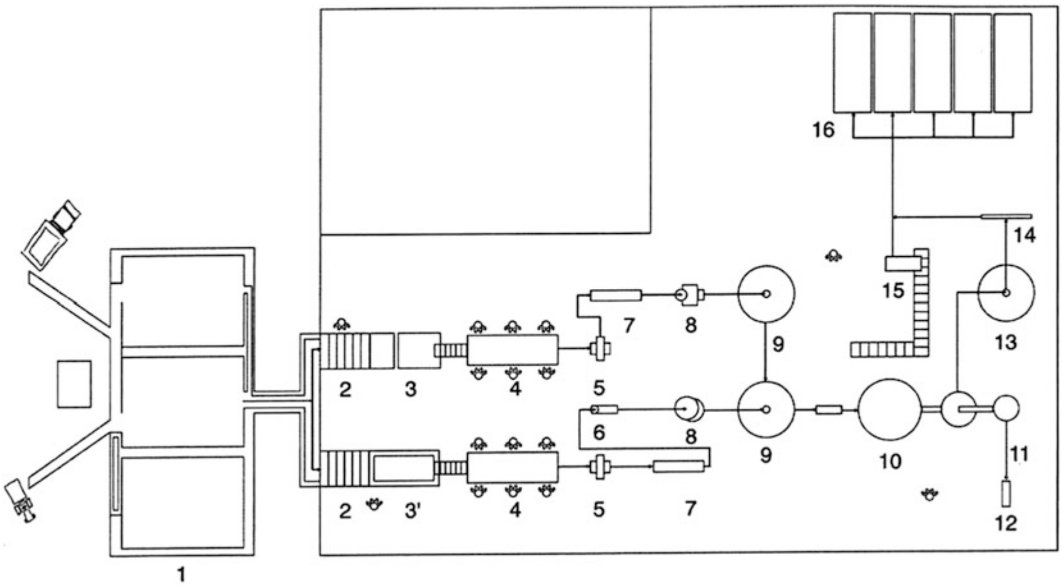


Fig. 10.3 Floor plan (layout of equipment) of a tomato-paste-processing plant (after Saravacos and Kostaropoulos 2002)

level of expertise underlying these systems can ultimately be expected to bring to the market place the CAPD technology that the food process engineering community needs to apply to be competitive in its own arena. Currently, research in this area is primarily focused on optimization methods and tear-stream techniques for solution of recycle problems.

Food process design programs tend to be application- or process-type specific. Application specific programs focus on the design of processes for a particular food commodity. In recent years, the development of computer-aided engineering software for use in the food industry programs has been extensive. Some of these programs have been described by Ötles and Önal (2004).

The following sections describe briefly a selection of software packages of potential interest to food manufacturers. The list is not intended to be exhaustive; rather it provides the reader with a range of typical programs. They are classified according to their primary use, namely, Process and Equipment Design (Sect. 10.4.2), Plant Operation (Sect. 10.4.3), and Product Development (Sect. 10.4.4). Table 10.4 provides details of their developers and Web sites.

10.4.2 Food Process and Equipment Design Packages

Large commercial baking companies are using *SolidWorks* to specify the design of commercial equipment in small bakery kitchens and large plants in more than 100 countries. This software can be used to design everything from the equipment that mixes the batter and pours it into the baking pans to the equipment that removes the excess flour from a freshly baked loaf of bread.

Simulink is an interactive tool for modeling, simulating, and analyzing dynamic, multidomain systems. It lets you build a block diagram, simulate the system's behavior, evaluate its performance, and refine the design. *Simulink* integrates seamlessly with *MATLAB*, providing you with immediate access to an extensive range of analysis and design tools. *Simulink* is widely used in control-system

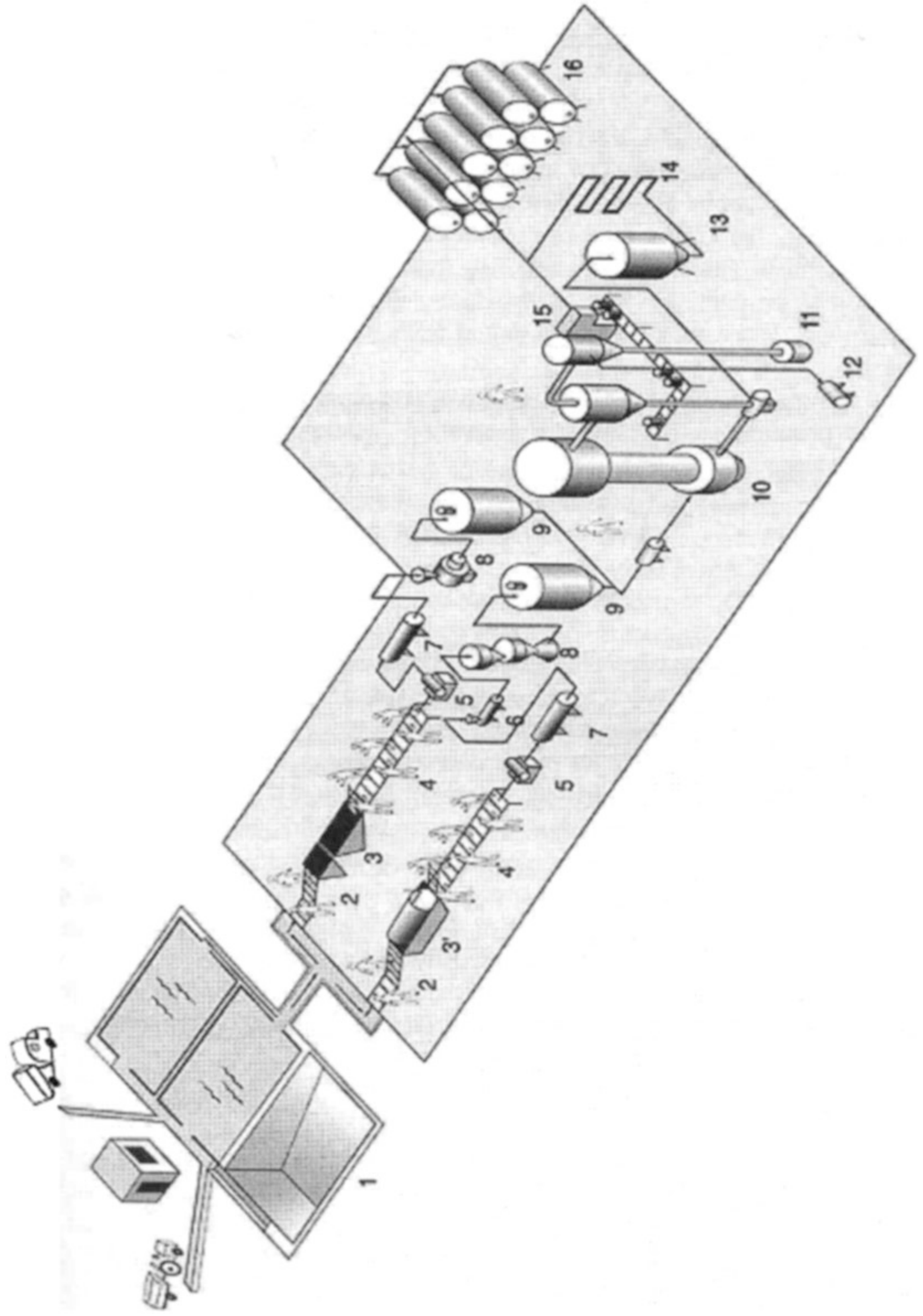


Fig. 10.4 Simplified 3D process flow diagram for a tomato-paste-processing plant (after Saravacos and Kostaropoulos 2002)

Table 10.3 Commercial and academic computer-aided flowsheeting packages for chemical engineering (adapted from Winter 1992)

Software	Developer	Web site
Ascend	Carnegie-Mellon University, Pittsburg, PA	http://ascend4.org/Main_Page
Aspen Plus	AspenTech, Burlington, MA	http://www.aspentech.com/core/aspen-plus.aspx
ChemCad	Chemstations, Houston, TX	http://www.chemstations.net/
Design II	Chemshare, Houston, TX	http://www.chemshare.com
Mirror model	Chemshare, Houston, TX	http://www.chemshare.com
Diva	University of Stuttgart, Germany	http://masters.donntu.edu.ua/2001/fvti/sisyukin/lib/1.htm
Hysys	AspenTech, Burlington, MA	http://www.aspentech.com/core/aspen-hysys.aspx
Process (Pro II)	Invensys Process Systems (IPS), Plano, TX	http://iom.invensys.com/EN/Pages/SimSci-Esscor_Process EngSuite.aspx

Table 10.4 Selected list of software of relevance to food manufacturers

Software	Developer	Web site
Food process and equipment design packages		
SolidWorks	Dassault Systemes, Vélizy-Villacoublay, France	http://www.solidworks.com
Simulink	The MathWorks, Natick, MA	http://www.mathworks.com/products/
FOODS-LIB	US Department of Agriculture	
Costherm	EU	http://www.nelfood.com
Pathogen Modeling Program	US Department of Agriculture	http://www.usda.gov
SuperPro Designer	Intelligen, Inc., Scotch Plains, NJ	http://www.intelligen.com
Plant operation software		
CALSoft	TechniCAL, Kenner, LA	http://www.tcal.com/
LIMS	Progeny Software, South Bend, IN	http://www.progenygenetics.com/
ERP	QAD, Santa Barbara, CA	http://www.qad.com
HighJump	HighJump Software, Eden Prarie, MN	http://www.highjump.com/
MES	Matrix Automation, Huron, OH	http://www.matrixautomation.com/
iBOLT Integration Suite	MagicSoftware, Laguna Hills, CA	http://www.magicsoftware.com/
The Unscrambler On-Line Classifier	CAMO Software Inc., Woodbridge, NJ	http://www.camo.com/
Product development software		
Genesis R&D SQL	ESHA Research, Salem, OR	http://www.esha.com/genesissql/
The Food Processor SQL	ESHA Research, Salem, OR	http://www.esha.com/foodprosql/
Cake Expert System	Campden BRI, Chipping Campden, UK	http://www.campden.co.uk
Bread Advisor	Campden BRI, Chipping Campden, UK	http://www.campden.co.uk
Flavor Creator 3.5	Flavor Knowledge Systems (fks), St Louis, MO	http://www.fks.com/software.aspx
Flavor Selector 5.0	Flavor Knowledge Systems (fks), St Louis, MO	http://www.fks.com/software.aspx
GRASbase 6.0	Flavor Knowledge Systems (fks), St Louis, MO	http://www.fks.com/software.aspx
WinCHEM	Selerant Corp., Milan, Italy	http://www.foodtech-international.com/suppliers/selerant/selerant.htm
ProductVision Formula Management	Advanced Software Designs (ADS), Chesterfield, MO	http://www.asdsoftware.com/

design, digital signal processing (DSP) design, communications system design, and other simulation applications.

FOODS-LIB software enables the following activities to be undertaken: flowsheeting and design of food processes, simple microbial and quality assessment, and economic analysis. The aim is to modularize a series of food safety concepts so that the user can adapt these tools to model any real food processing system. The software integrates food safety issues into the specification of unit operations and process design.

A software package, *COSTHERM*, was developed in the 1990s under the EU-funded PECO project on the Thermophysical Properties and Behaviour of Foods. The program can be used to predict thermal properties of foods as a function of their chemical composition and temperature. The EU database of agro-food materials is available on-line at http://www.nelfood.com. As of 2003, this database contained over 11,000 bibliographic records, about one in five of which has numerical tables or equations attached (Rao et al. 2005).

Pathogen Modeling Program, a predictive microbiology application, was designed by the US Department of Agriculture—Agriculture Research Service as a research and instructional tool for estimating the effects of multiple variables on the growth, inactivation or survival of food borne pathogens.

BATCHES is a batch process simulator that has found applications in pharmaceutical, biochemicals, and food processing. It is especially useful for fitting a new process into an existing facility and analyzing resource demand as a function of time. *BATCHES* allows the user to evaluate alternative system configurations and operating procedures, to size process equipment, and to evaluate scheduling strategies.

SuperPro Designer facilitates modeling, evaluation and optimization of integrated processes in a wide range of industries (pharmaceutical, biotech, specialty chemical, food, consumer goods, mineral processing, microelectronics, water purification, wastewater treatment, air pollution control, etc.). The combination of manufacturing and environmental operation models in the same package enables the user to concurrently design and evaluate manufacturing and end-of-pipe treatment processes and practice waste minimization via pollution prevention as well as pollution control. *SuperPro Designer* handles material and energy balances, equipment sizing and costing, economic evaluation, environmental impact assessment, process scheduling, and debottlenecking of batch and continuous processes.

10.4.3 Plant Operation Software

The CALSoft software was developed by TechniCAL specifically for designing heat penetration and temperature distribution tests in retorts, evaluating the collected data, and calculating a thermal process or vent schedule/come-up time.

LIMS (Laboratory Information Management System) is a powerful, full-featured, highly extensible, and scalable laboratory information system. It is used by corporate, government, municipal, and private laboratories worldwide to maintain records of, for example, their chemical, clinical, environmental, food, and forensic analyses. The program is widely used in the petrochemical and pharmaceutical industries.

Enterprise Resource Planning (*ERP*) is a software system that is employed by many organizations, particularly those having the necessary IT skills, to coordinate on a company-wide basis all aspects of their supply chain management, manufacturing operations, human resource management, etc. *ERP* systems are based on a common database, which is accessible by all departmental functions in real time. The modular construction of *ERP* software provides the necessary flexibility to meet the needs of multiple users and to adapt to the inevitable changes (e.g., to products, suppliers, and customers) over the lifetime of the system. Wikipedia (2009) lists available free, open source and proprietary *ERP* software.

HighJump Software is a leading supplier of supply chain execution software with a claimed 1,300 users in ten countries. Food and beverage companies employ *HighJump* to manage their inventories and provide access to real-time critical information from source to consumption. The program employs a flexible architecture that permits the user to adapt to changing business needs without excessive cost or disruption.

Manufacturing Execution System (*MES*) software is a tool for the company to use to meet the production, quality and growth goals. It optimizes the management and execution of the plant floor production processes and can be tailored to meet the plant or company requirements. *MES* compliments existing business and manufacturing systems and supports initiatives like demand-flow technology (DFT) and lean manufacturing.

The *iBOLT Integration Suite* delivers a complete integration and development framework that provides users with the ability to quickly integrate a wide range of business applications. The program enables users to increase the efficiency, usability and life span of their existing systems while integrating new technologies and applications.

The *Unscrambler On-Line Classifier* (*OLUC*) is an application allowing Unscrambler classification models to be run automatically on data collected from the production line instruments thereby resulting in improved process control.

10.4.4 Product Development Software

Genesis R&D SQL is a widely used North American nutritional labeling program. In addition to the nine Nutrition Labeling and Education Act (NLEA) label formats and a supplement label, a variety of professional reports are available. These can be viewed as a spreadsheet, protein quality report, bar graph comparison, or single nutrient report.

The Food Processor is an easy-to-use nutrition analysis system, which may be used to create recipes and menus, aid in conducting medical research and in counseling for dietary deficiencies and excesses. This software features a comprehensive database and food selection guide.

Campden BRI (http://www.campden.co.uk) has developed a series of software programs to aid in the development of cake and bread recipes. *Cake Expert System* comprises three modules:

- *BALANCE* enables product developers design new cake products, by examining and adjusting ratios of ingredients so that they fall into an acceptable range for the product sought.
- FAULT DoC provides a tool for flour confectionery production fault diagnosis and product optimization.
- *ERH CALC* allows users to calculate water activity and to predict the minimum mold-free shelf life of a product.

Bread Advisor enables users diagnose faults, enhance product quality, and check out processing steps and settings. It can also be used as a training tool.

Flavor Knowledge Systems (fks) has developed a suite of software to assist in flavor creation. *Flavor Creator 3.10* reduces the time taken by flavorists to create flavors from over 1,000 available flavor ingredients for which qualitative and quantitative sensory data are available. *Flavor Selector 5.0* is a flavor-information management database designed to develop or maintain a flavor library. It contains all information that characterizes flavors including sensory profiles. Finally, *GRASbase 6.0* is a flavor ingredient reference database, containing 2,423 additives through GRAS 23. It includes regulatory reference numbers for preservatives, anti-caking agents, food additives, and FDA approved flavor ingredients. The software features comprehensive query, retrieval, and reporting facilities.

WinCHEM is a comprehensive package developed for the development of food formulations:

- *EuSheet* (Flavors and Fragrances) has been specifically developed for the creation of Safety Data sheets.
- *EuFormula* (Flavors and Fragrances) calculates and organizes chemical formulations.
- *EuFlavor* is a program, specially designed for flavoring manufacturers, for fast and simple formula classification and for production of ingredient lists complying with EU Directive 88/388 (EC 1988).
- *EuPRINT* is used for producing, handling, and printing health hazard labels for substances and compounds.

ProductVision Formula Management (FM) is a Windows-based product development program available to the food and beverage and cosmetics industries. This software streamlines formula management with automatic calculation of all nutrition property and costing information. *FM* also offers versatile formula development, costing, and laboratory analysis tools in a scalable client–server environment.

10.5 Illustrative Examples of the Use of Selected Software

10.5.1 Simulation of a Milk-Processing Plant Using SuperPro Designer

This example deals with an integrated milk processing plant that produces cheese, butter, whey protein concentrate (WPC), and food-grade ethanol. The example is taken from Intelligen's databases and is based on data that are available in the literature (Morris 1986; Zaror and Pyle 1997). It serves to illustrate the capabilities of computer-aided process design.

Figures 10.5 and 10.6 show the process flowsheet of the specified process. The plant operates around the clock for 330 days a year. On a daily basis it processes 2,000 metric tons of milk (83,333 kg/h) and produces 214 tons of cheese, 9 tons of butter, 211 tons of WPC, and 33.5 tons of 95 % (by mass) ethanol.

The concept of flowsheet sections was introduced as part of *SuperPro Designer* release 3.0 to facilitate reporting of results for costing, economic evaluation, and raw material requirements of integrated processes. A flowsheet section is a group of process steps that have something in common. The plant in this example consists of four sections: Cheese-Making, Butter-Making, WPC-Making, and Ethanol-Making.

10.5.1.1 Process Description

1. Cheese Production
   Milk is pumped from tankers into any of six identical 227 m^3 (60,000 gal) silos (V-112), which are each mounted on load cells to monitor the level of milk at any given time (Fig. 10.5). Note that these six silos are represented by one icon on the flowsheet. Other sets of identical equipment items, operating in parallel, are represented by single icons as well. The temperature in the silos is maintained at around 4 °C. Milk from the silos flows through a pasteurizer (heat exchanger), HX-101, which is operated at around 68 °C. The milk then flows through a cooler (HX-102) to reduce its temperature at the inlet to the cheese vats (V-102) to 30 °C. Lactic-acid starter culture and rennin are added in small proportions

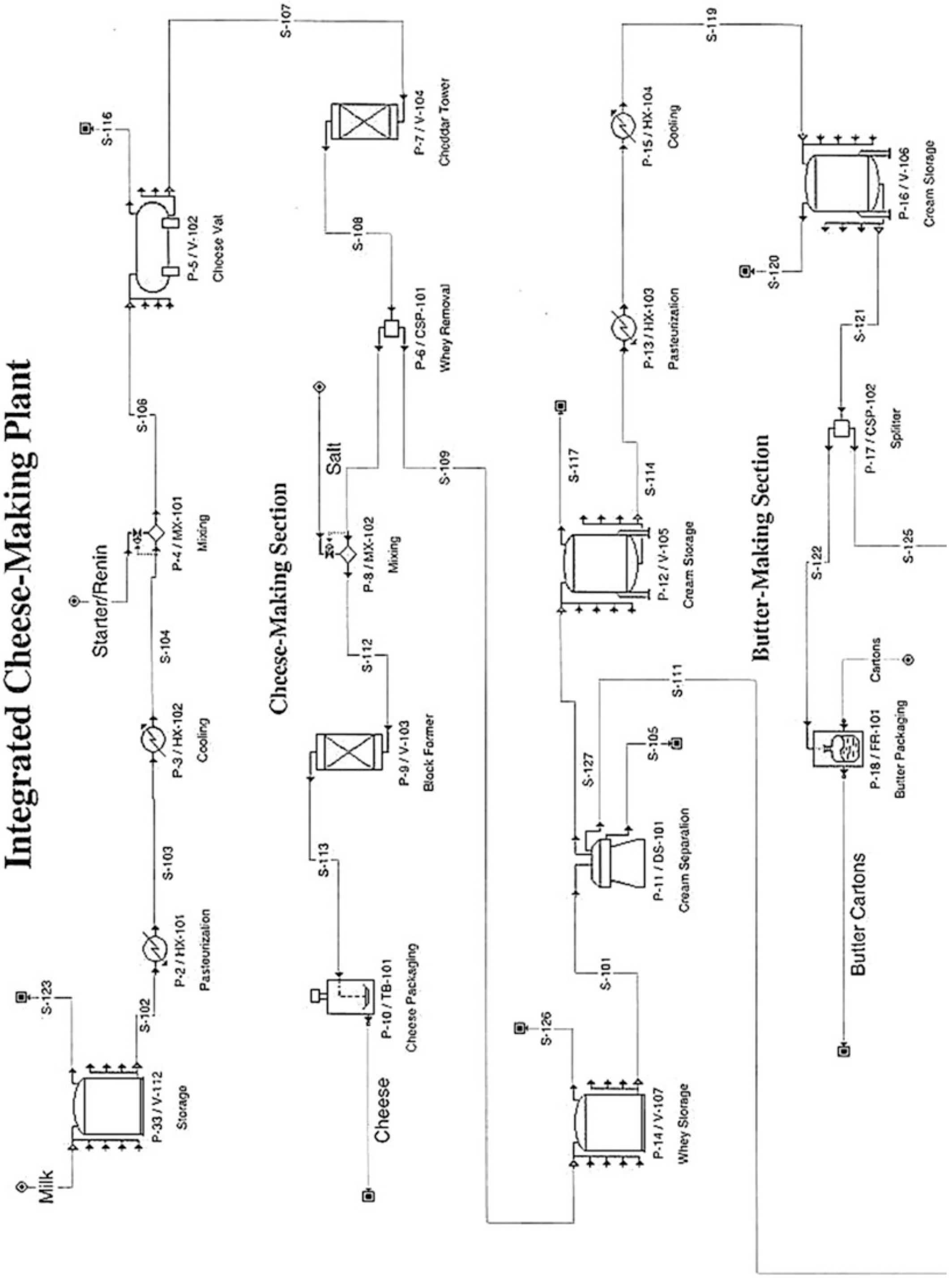


Fig. 10.5 Process Flow diagram for cheese production using *SuperPro Designer*

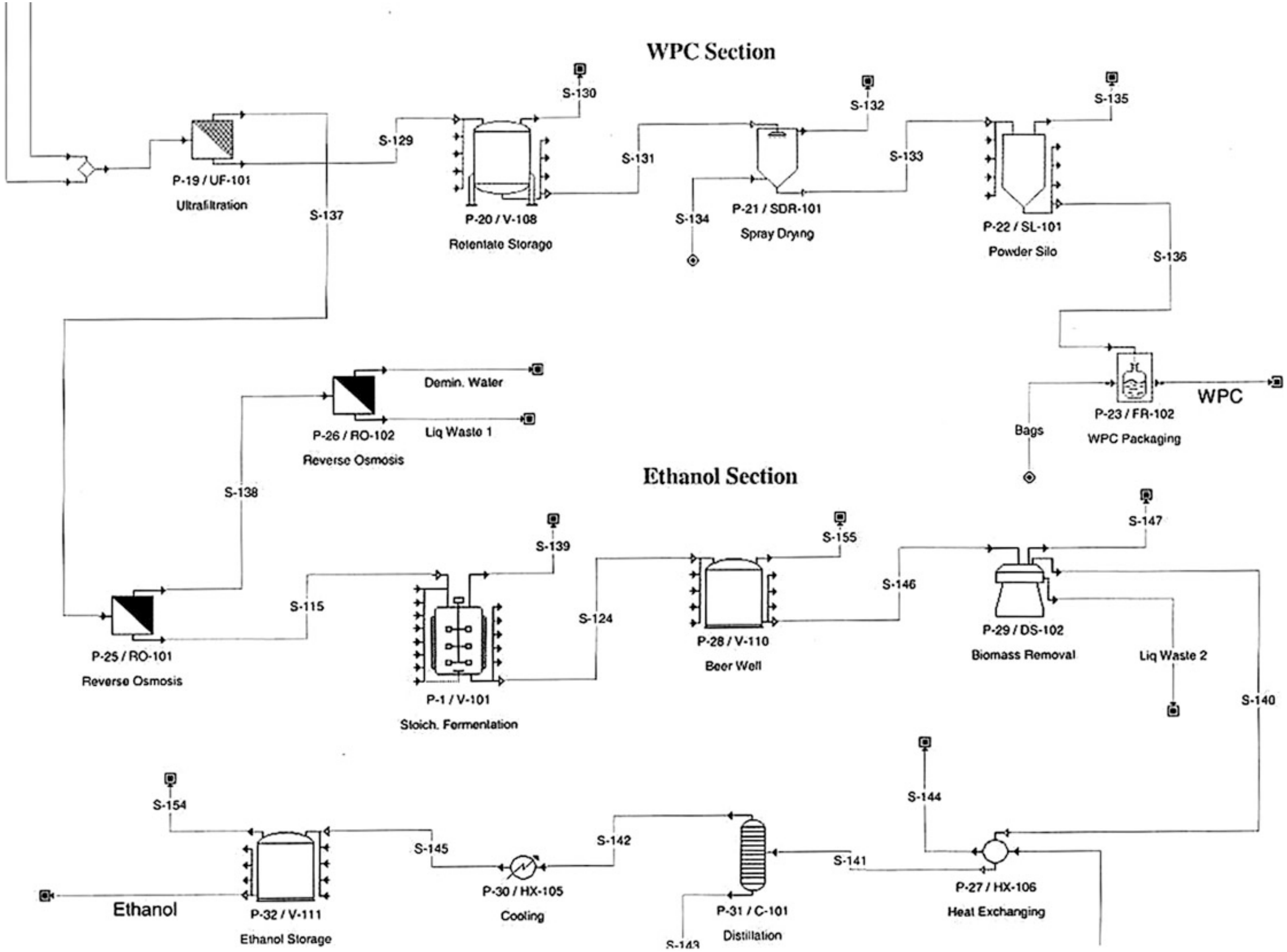


Fig. 10.6 Process Flow diagram for cheese production using *SuperPro Designer* (continued)

to the contents of the vats. Next, the curd is solidified for 2 h in the cheddar tower (V-104). Then the aqueous whey stream (S-109), is removed (CSP-101). The whey stream is composed of unconsumed proteins, fat, lactose, mineral salts, and water. Next, salts are added in MX-102. Stream S-112 is then fed to the block former (V-103) where the cheese is formed into blocks. After block formation, the cheese is sealed (TB-101), cooled and stored to mature.

2. Butter Production
   Using three centrifugal separators (DS-101), the whey stream (S-101) is separated into a fat-rich cream (S-127) and a dilute aqueous stream (S-111) containing mainly proteins, salts, and lactose. The cream is pasteurized as before (in HX-103 and HX-104) and used as the feed for making Grade B butter, which is the highest possible grade for whey butter. The butter is packaged in cartons (FR-101), which contain 30 kg of material. In addition, the butter whey stream (S-125) is combined with the dilute aqueous stream (S-111) from the centrifugal separators and is sent to the WPC section.
3. Whey Protein Concentrate (WPC) Production
   The dilute aqueous streams (S-125 and S-111) from the Butter-Making section contain two other potentially valuable components, albeit in low concentrations: whey proteins and lactose. The whey proteins are concentrated using crossflow ultrafilters (UF-101), and then spray-dried (SDR-101) to produce solid WPC containing 50–75 % protein (see Fig. 10.6). The dried WPC is stored in silos (SL-101) and packaged in bags containing 22.5 kg (50 lbs) of material.
4. Ethanol Production
   The liquid permeate from the ultrafilters (stream S-137) is treated using reverse osmosis units (RO-101). The concentrate stream from these units retains lactose and most of the mineral salts. The permeate stream (S-138) goes through another reverse osmosis system (RO-102) to remove residual minerals. The result is pure demineralized water, which is recycled as CIP sanitizing and rinse water. Approximately 33.5 % of the water contained in the original milk is recycled this way. The concentrated lactose solution from the first RO system (stream S-115) is fed to any of three fermenters (V-101), where a proprietary strain of yeast is used to produce ethanol. The resulting "beer" solution, which is 4–5 % alcohol (by mass) at this point, then flows into one of two beer wells (V-110). Next, the beer solution is sent to a centrifugal separator (DS-102), which recovers and recycles the yeast. The biomass-free permeate (stream S-140) is then preheated in heat exchanger HX-106 before distillation. Heat-exchange integration is used to warm the incoming solution (stream S-140) using the bottoms stream from the distillation column (stream S-143). Next, the dilute ethanol solution is concentrated by distillation (C-101) to spirit-grade levels. The distillation process step is a typical three-stage system employing thermal vapor recompression to recover steam and using glycol to break the azeotrope in the first stage. This boosts the alcohol from 180 to 198 proof.

10.5.1.2 Material Balances

Table 10.5 provides information on raw material requirements for the entire flowsheet. The quantities are displayed in kg/year, kg/h, and kg/MP Entity (MP Entity = Main Product Entity = 18 kg cheese block). The table was extracted from the Excel version of the *SuperPro Designer* Stream Report.

Table 10.6 was taken from the Excel version of the Environmental Impact Report. It provides information on the amount of each component that enters the plant, and displays the amount of each that ends up in waste streams. In this process, the utilization of lactose is around 91 %. In terms of water, around 61 % of the incoming water (contained in the milk) ends up in waste streams. The rest is recovered as demineralized water (around 33.5 % of the total) or remains in the final products (as the water content of cheese and butter). Overall, the plant is quite effective from an environmental impact point of view.

Table 10.5 Raw material requirements for milk processing plant

Raw material	kg/year	kg/h	kg/MP entity
Starter	6,599,974	833.3	1.681
Rennin	659,997	83.3	0.168
Salts	1,412,806	178.4	0.360
Milk	659,997,360	83,333.0	168.109
Air	123,227,008	15,559.0	31.387
Flowsheet total	791,897,144	99,987.0	201.706

Table 10.6 Comparison of component flows entering milk processing plant with those leaving in liquid effluent streams

	Total in (kg/h)	Out as liquid waste (kg/h)
Anions	333.3	311.2
Casein	2,250.0	0.0
Cations	250.0	233.4
Ethyl alcohol	0.0	320.2
Fats	3,250.0	0.0
Lactose	4,083.3	381.2
Nitrogen	11,935.6	0.0
Oxygen	3,623.4	0.0
Paper	3.9	0.0
Plastic	12.3	0.0
Rennin	83.3	0.0
Salts	178.4	0.0
Starter	833.3	0.0
Water	72,666.4	44,335.5
Whey	500.0	0.0
Yeast	0.0	343.1
Plant totals	100,003	45,925

Table 10.7 Economic evaluation of milk processing plant

Total capital investment	115,855,000	$
Operating cost	173,353,000	$/year
Production rate	3,926,000	Entities/year in Cheese
Unit production cost	45	$/Entity in Cheese
Total revenues	266,443,000	$/year
Gross margin	34.94	%
Return on investment	56.18	%
Payback time	1.78	Years
IRR after taxes	46	%
NPV (at 7.0 % interest)	358,258,000	$
Entity = Cheese block (18 kg)		

10.5.1.3 Cost Analysis and Economic Evaluation

The essential results of the cost analysis for the entire flowsheet are shown in Table 10.7. This gives an overview of the total economic impact of the plant, including the total capital investment, yearly revenues, and rate of return. These data were exported from the Economic Evaluation Report. This information (along with additional data) also appears in the Executive Summary dialog.

To calculate the revenues for this process, the following prices were assumed for the product and by-products of the plant: cheese is sold for $2.5/kg ($45/block), butter is sold for $2/kg ($80/carton), WPC is sold for $0.89/kg ($20/bag) and ethanol is sold for $0.9/kg. Table 10.8 displays the total annual revenue generated by these products.

Table 10.8 Breakdown of revenues from milk processing plant

Revenue from	$/year
Cheese	176,670,000
WPC	61,961,000
Ethanol	9,948,000
Butter	5,939,000
Total	254,518,000

Table 10.9 Annual operating costs of milk processing plant

Cost item	Cheese section ($/year)	Butter section ($/year)	WPC section ($/year)	Ethanol section ($/year)	Subtotal ($/year)	%
Raw materials	140,782,077	1,266,068	44,079	0	142,092,225	81.97
Equipment	2,115,394	1,849,382	5,735,247	8,524,209	18,224,234	10.51
Labor	622,987	541,015	704,959	1,344,341	3,213,302	1.85
Consumables	0	0	1,633,686	680,702	2,314,388	1.34
Lab/QC/QA	93,448	81,152	105,744	201,651	481,995	0.28
Waste Trt/Dsp	0	0	0	1,709,273	1,709,273	0.99
Utilities	974,626	525,422	1,481,157	2,335,921	5,317,127	3.07
Transportation	0	0	0	0	0	0.00
Miscellaneous	0	0	0	0	0	0.00
Subtotal	144,588,533	4,263,041	9,704,872	14,796,097	173,352,543	100.00
Contribution (%)	83.41	2.46	5.60	8.54	100.00	

Table 10.10 Breakdown of raw materials costs for milk processing plant

Raw material	Unit cost	Annual amount	Cost	
Bulk	*($/kg)*	*(kg)*	*($/year)*	*%*
Starter	0.82	6,599,974	5,411,978	3.84
Rennin	5.00	659,997	3,299,987	2.34
Salts	0.05	1,412,806	70,640	0.05
Milk	0.20	659,997,360	131,999,472	93.66
Discrete	*($/Entity)*	*(# of Entities)*	*($/year)*	*%*
Empty carton	1.00	97,092	97,092	0.07
Empty bags	0.20	310,184	62,037	0.04
Total		140,941,000	100	

Table 10.9 gives a summary of the annual operating costs; it was extracted from the Excel version of the Itemized Cost Report for this example. As can be seen from this table, raw materials contribute 82 % of the total operating cost, followed by equipment-dependent costs (10.5 %), labor (1.85 %), and utilities (3.07 %). The unit cost of milk was assumed to be \$0.2/kg (\$0.8/gal). The milk expense represents roughly 94 % of the total raw material cost (see Table 10.10). The equipment-dependent costs for this process comprised depreciation, maintenance, and miscellaneous equipment expenses. Labor costs were based on the sum of the labor requirements for each unit procedure multiplied by a fixed labor rate, which was based on a basic labor rate, plus adjustments for fringe benefits, administration, etc. Utility costs were based on the type of heat transfer agent used, and the heating/cooling requirements. Table 10.10, which was extracted from the Excel version of the Economic Evaluation Report, also provides information on the contribution of each flowsheet section to the total operating cost. As can be seen, the cheese-making section contributes around 83.4 % of the total cost, followed by ethanol-making (8.54 %), WPC-making (5.6 %), and butter-making (2.46 %).

10.5.2 Simulations Using BATCHES

10.5.2.1 Introduction

Many food manufacturing operations fall under the category of batch/semi-continuous processes. The key features of this mode of operation have been discussed by Clark and Joglekar (1996a, b). Some of the features of batch/semi-continuous processes are accommodated in conventional discrete event simulation methodology (event calendar, time advance mechanism, task dispatching logic and Monte Carlo sampling); while other features require continuous dynamic simulation techniques (state event detection, solution of differential/algebraic equations). The resulting hybrid methodology combines discrete and dynamic simulation.

Hybrid simulators provide a framework for building a general, scalable recipe, which is defined as the sequence of operations performed in converting raw material to finished product. A general recipe describes product-specific processing information, and is created without specific knowledge of the equipment used in the manufacturing process (ANSI/ISA-S88 1995). It provides details on each operation, the sequence of steps within each operation, material and resource requirements for each step, the duration of each step, and so on. Specific rules to be followed by the production personnel are also included as part of a product recipe.

The publication of the S88 batch control standards (ANSI/ISA-S88 1995) was the first attempt to formalize a structure for defining recipe information. By proposing a common terminology, these standards brought uniformity to recipe descriptions and facilitated the exchange of information. The modeling constructs of the *BATCHES* simulator are ideally suited for using general recipes as outlined in the S88 batch control standards. Thus, if general recipes already exist, a simulation model can be set up to interface with it and extract the appropriate information for use in applications. On the other hand, a *BATCHES* recipe model can be translated into a general recipe for use by batch control systems.

In the following sections, two plant-level case studies of food processing operations using the *BATCHES* simulator will be briefly described. These case studies illustrate the benefits of using simulation in evaluating various alternatives, which provide a quantitative basis for making strategic and operating level decisions.

10.5.2.2 Example 1: Meeting Increased Demand in Milk Production

The sales organization of a liquid dairy plant predicts a 64 % increase in the total demand of two of its whole milk products: 1-Gallon Homogenized milk and 1-Gallon brand name product VITA milk. The best alternative for meeting the projected increase in demand is to be selected.

The key processing stages in the fluid dairy plant are pasteurization, intermediate storage and packaging. A schematic diagram of the process equipment in these stages is shown in Fig. 10.7. The pasteurization step is performed in two HTST (high-temperature short-time) heat exchangers. The pasteurized intermediates are stored in 21 surge tanks. The 12 fillers downstream of the surge tanks are dedicated to specific container sizes (1 gal, ½ gal, quart, pint, and so on). In this study, the manufacture of six intermediates and 36 filled products was considered.

The following are some of the key operating features of the existing dairy plant. The product slate and the amount of each product made are different for each day. The daily production is completed in approximately 20 h. The sequences in which the intermediates are made minimize the amount of cleaning of the pasteurizers. The fillers stop frequently due to mechanical breakdowns or when cartons get jammed in the machines. The assignment of a pasteurizer to process an intermediate is governed by the intermediate type. For example, the different grades of chocolate milk and

Fig. 10.7 Schematic diagram of milk pasteurization and packaging operations

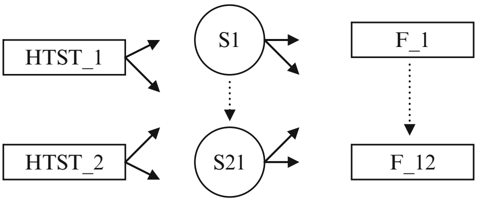


Table 10.11 Results of *BATCHES* simulation of liquid milk production plant

Run	Conditions	Makespan (h)
1	Base case. Total production 135,879 gal/day. (1G Homogenized 47,400 and VITA 1G 16,800 gal)	19.7
2	New demand. No changes to the facility. (1G Homogenized 76,300 and VITA 1G 28,900 gal)	29.4
3	Add one 1 gal filler and one HTST	19.0
4	Add one 1-gal filler. Delay filler startup by 1.5 h (Only 2 HTSTs as in base case)	19.2

buttermilk are processed only on pasteurizer HTST_2. The increase in daily production of 1-Gallon Homogenized milk from 47,400 to 76,300 gal, and that for VITA 1G from 16,800 to 28,900 gal were studied. Both the products are packaged in 1-gal cartons filled on the same filler.

The results of the process simulation are summarized in Table 10.11. As may be seen, with the current demand, the predicted production time (Run 1) is 19.7 h, which is in close agreement with practice.

Run 2 shows that it is not possible to meet the increased demand without making any changes to the process as it requires a production time of 29.4 h. The effect of adding an additional 1-gal filler in parallel with the existing fillers was then explored. This was shown to create an imbalance in the pasteurizer and filling line throughputs thereby forcing the fillers to stop and start frequently. This problem could be resolved by adding a third pasteurizer (Run 3); this reduced the production time to an acceptable 19.0 h. Alternatively, the problem could also be solved by creating a buffer stock of 20,000 gal by delaying the start-up of the 1-gal fillers by 1.5 h with respect to the pasteurizers (Run 4). The required production time in this case is 19.2 h. The latter is the preferred solution as the required 64 % increase in demand for the two products could be accommodated without the need to install an additional HTST.

10.5.2.3 Example 2: Yogurt and Cottage Cheese Production Process

This multiproduct process consists of raw milk receiving, skim milk, cottage cheese, yogurt and sour cream (SC) preparation sections. Additionally, the following shared resources are used in the process: Cleaning-In-Place (CIP), tap water, hot water, steam, electricity and refrigeration. Four CIP skids are available; each skid is limited to a certain set of equipment items. A typical CIP cycle consists of a wash with tap water, following by washes with caustic, tap water and acid. After the acid wash, the piece of equipment is cleaned with steam.

A *BATCHES* simulation model of the process was constructed. The recipe diagrams for cottage cheese and yogurt manufacturing are shown in Fig. 10.8. Brief process descriptions for these products are as follows.

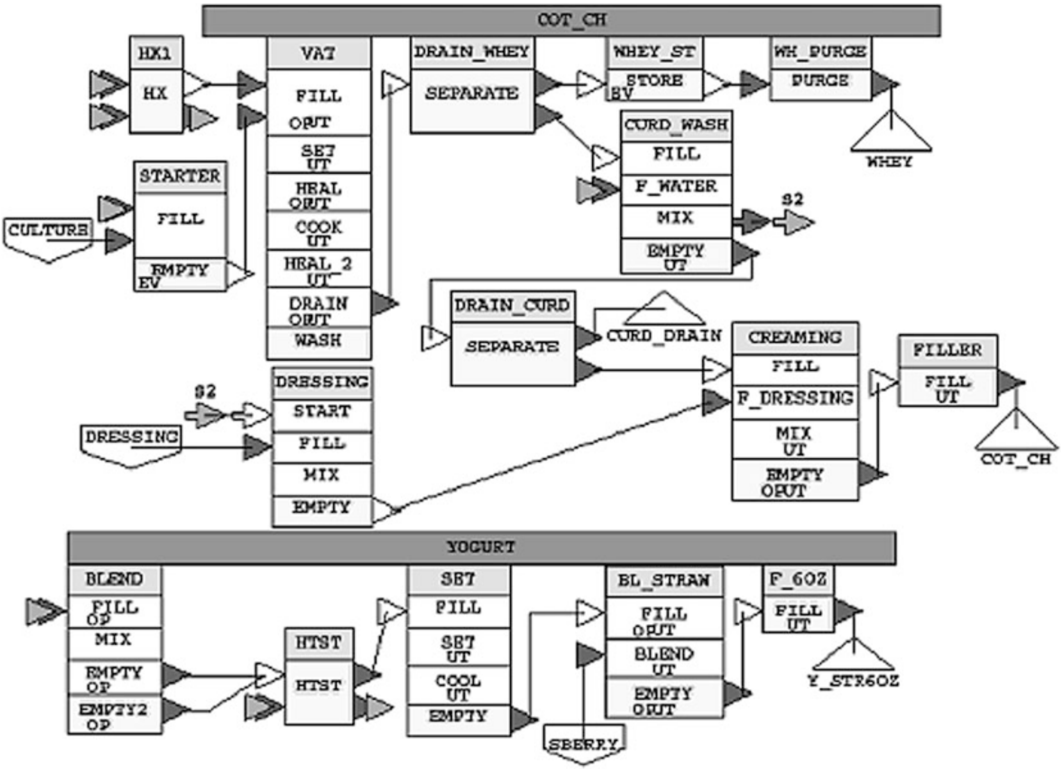


Fig. 10.8 Recipe diagram for *BATCHES* simulation of a yogurt and cottage cheese production process

1. Cottage Cheese Production
   In a vat, skim milk and a predetermined amount of culture are added. The material is then heated, cooked and cured. The whey is drained, and the curd is washed with water. The curd is mixed with a batch of dressing, and is subsequently fed to the fillers.
2. Yogurt Production
   Predetermined amounts of skim milk are added to the yogurt vats. After it is set, the yogurt is blended with the desired fruit, and then fed to the fillers. The sour cream recipe is very similar to the yogurt recipe.

The base case model was used to verify the current weekly production of sour cream and yogurt at about 1.285 million pounds. By adding four 6,000 gal vats, to be used for sour cream manufacture, weekly production can be increased to 2.078 million pounds. The Gantt charts for the base case and the case with the additional vats are shown Figs. 10.9 and 10.10, respectively. They show the operation for a 48.0 h window covering days 2 and 3.

In the modified process, the pasteurizer utilization increases from 50 % to 80 % and the utilization of the fillers also goes up considerably with the addition of new vats. Note that the existing CIP system was adequate to handle the additional vats. In both cases, the filler F6OZ is halted for a short while when an upstream blend tank becomes empty and the connection is switched to another blend tank. This results in numerous small boxes in the Gantt chart for F6OZ, each box representing the time required to empty the blend connected to it.

Additionally, the shared resources used in the process, namely, CIP, tap water, hot water, steam, electricity, and refrigeration, can be predicted for each of the scenarios. Constraints can be placed on

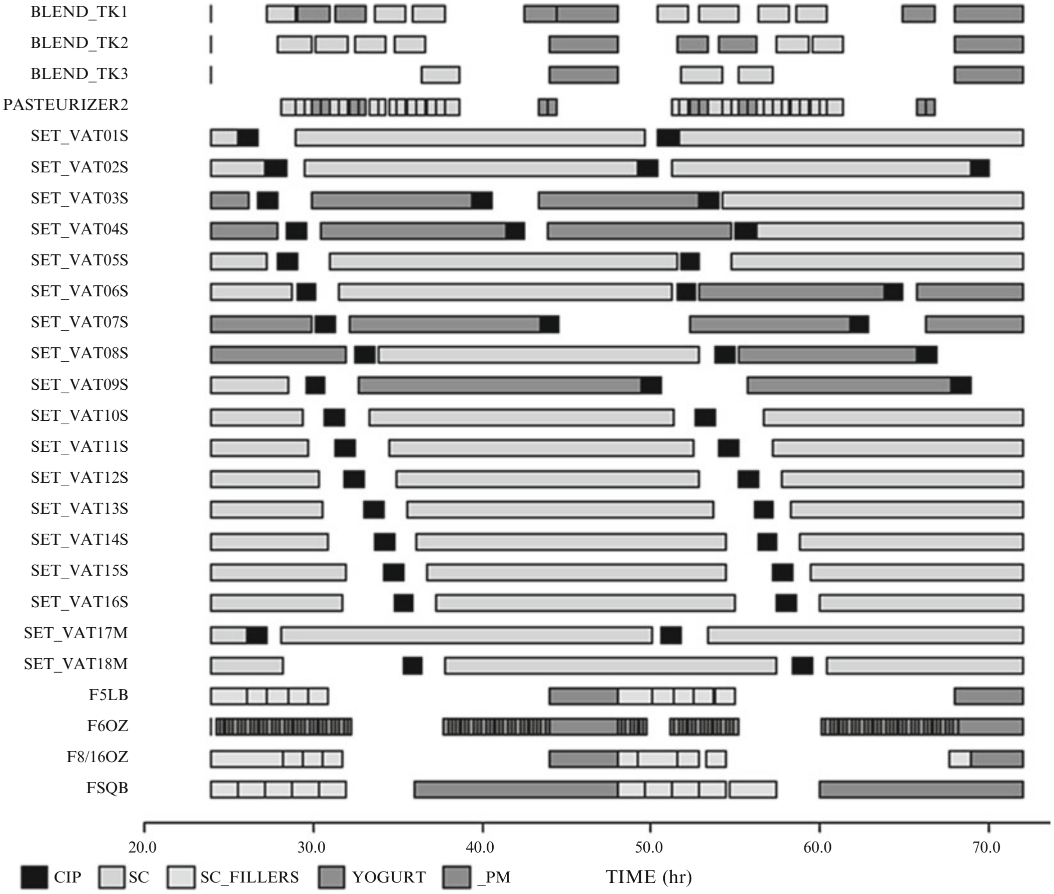


Fig. 10.9 Recipe-based Gantt chart for the BATCHES simulation of a yogurt and cottage cheese production process—Base case

each utility, which would then affect the production make span. Recycle, reuse, and reconditioning strategies can also be implemented to simulate zero discharge conditions.

10.6 Conclusions

In the chemical industry, the introduction of process simulators has brought about many benefits, not only in the design of plants but also in their operation. To a much more limited extent, similar benefits have accrued to the food industry through the use of simulators and other computer programs, particularly with liquid food plants, which are much easier to model than their solid-food counterparts. In this chapter, we have described a variety of software that can be used in the design and operation of food plants and in product development. Examples of the use of the design software are presented and serve to illustrate the benefits of this approach. Undoubtedly, current limitations due to the difficulties associated with the modeling of solids and the specification of individual food components will be progressively overcome.

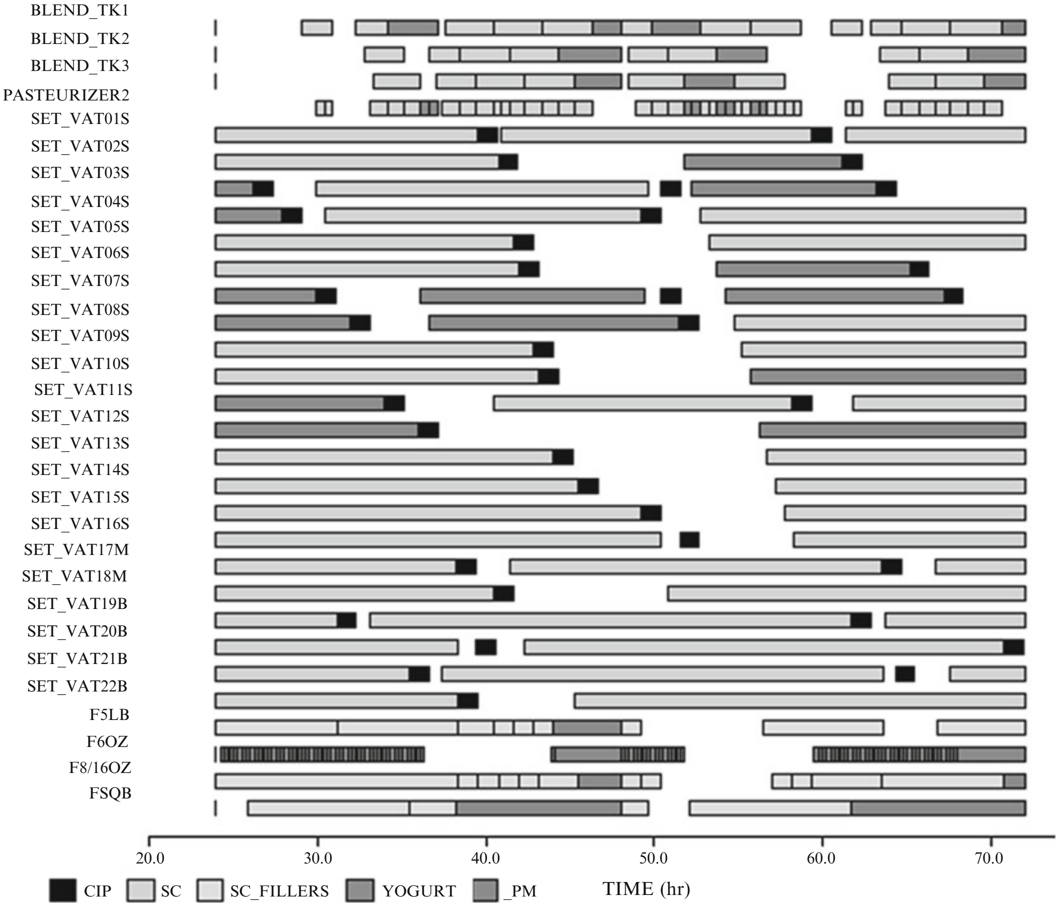


Fig. 10.10 Recipe-based Gantt chart for the *BATCHES* simulation of a yogurt and cottage cheese production process—case showing the effect of adding four additional vats (SET_VAT19b to SET_VAT22b) for sour cream production

References

ANSI/ISA-S88 (1995) “Standard batch control. Part 1: Models and terminology”, The International Society for Measurement and Control.

ChE (1999) “CAD improves on the basic”. Chemical Engineering, July: 109–110.

Chakroun, I., Isambert, A. and Depeyre, P. (1995) “Use of process static simulator for improving food data logging. Application to vegetable oil refining process”, Acta Chim. Slov., 42 (1), 21–26.

Clark, S.M. and Joglekar, G.S. (1996a) “Features of discrete event simulation” in “Batch processing systems engineering”,(eds) Reklaitis, G.V., Rippin, D.W.T., Hortacsu, O., Sunol, A.K., NATO ASI Series F, Springer Verlag, New York.

Clark, S.M. and Joglekar, G.S. (1996b) “Simulation software for batch process engineering” in “Batch processing systems engineering”, (eds) Reklaitis, G.V., Rippin, D.W.T., Hortacsu, O., Sunol, A.K., NATO ASI Series F, Springer Verlag, New York.

Datta, A.K. (1998) “Computer-aided engineering in food process and product design”, Food Technology, 52 (10), 44–52.

Diefes, H.A., Okos, M.R. and Morgan, M.T. (2000) “Computer-aided process design using Food Operations Oriented Design System Block Library”, Journal of Food Engineering, 46 (2), 99–108.

EC (1988) “Council Directive on 22 June 1988 on the approximation of the laws of Member States relating to flavours for use in foodstuffs and to source materials for their production”, European Commission. Available online at http://ec.europa.eu/food/fs/sfp/addit_flavor/flav09_en.pdf.

Fryer, P.J., Pyle, D.L. and Rielly, C.D. (1997) “Chemical engineering for the food industry”, Blackie Academic and Professional, London, 462 pp.

Maroulis, Z.B., and Saravacos, G.D. (2003) “Food process design”, Marcel Dekker, New York, 506 pp.

Ötles, S., and Önal, A. (2004) “Computer-aided engineering softwares in the food industry”, Journal of Food Engineering, 65 (2), 311–315.

Peters, M.S., Timmerhaus, K.D. and West R.E. (2003) “Plant design and economics for chemical engineers”, 5th edit., McGraw-Hill, New York, 988 pp.

Petrides, D.P. (1994) “BioPro Designer: An advanced computing environment for modeling and design of integrated biochemical processes”, Computers and Chemical Engineering, 18 (Suppl.), S261–S265.

Rao, M.A., Rizvi, S.S.H. and Datta, A.K. (2005) “Engineering properties of foods”, 3rd edit., CRC Press, Boca Raton, LA, 738 pp.

Saravacos, G.D. and Kostaropoulos, A.E. (2002) “Handbook of food processing equipment”, Kluwer Academic/ Plenum Publisher, New York, 698 pp.

Valentas, K.J., Rotstein, E. and Singh, R.P. (1997) “Handbook of food engineering practice”, CRC Press, Boca Raton, LA, 718 pp.

Wikipedia (2009) “List of ERP software packages”, http://en.wikipedia.org/wiki/List_of_ERP_software_packages.

Winter, P. (1992) “Computer-aided process engineering: The evolution continues”, Chemical Engineering Progress, 88 (2), 76–83.

Zaror, C.A. and Pyle, D.L. (1997) “Process design: an exercise and simulation examples” in “Chemical engineering for the food industry”, (eds) Fryer, P.J., Pyle, D.L. and Reilly, C.D., Blackie Academic and Professional, London, 461 pp.

Part II
Factory Infrastructure

Chapter 11
Site Considerations

K.P. Sutton

11.1 Introduction

The reality of building a factory to house a modern food plant will often become a series of compromises, particularly when a decision on the choice of site must be taken. The causes are the location, size, shape, form, and ultimately the cost of the chosen site.

From other Chapters (Chaps. 2–4), the process layouts will have been developed, with their associated requirements for raw material delivery and finished goods dispatch. These will enable the architect/surveyor to establish the minimum floor area required, optimum efficiency, room layouts, material movement routes, and staff movement routes.

In the present chapter, the factors influencing the choice of a suitable factory site are considered. The choice of geographic location is first addressed (Sect. 11.2). The possibility of using an existing facility is then discussed in Sect. 11.3. Finally, the factors that should be considered when selecting brown- and green-field sites are described in Sect. 11.4.

11.2 Geographic Location of Factory Site

Several factors have resulted in today's food industry becoming truly international. Naturally, mergers and acquisitions have played an important role as companies seek to achieve the economies of scale. However, the lowering of trade barriers in, for example, the NAFTA countries and the European Union, improvements to transportation infrastructures, and the harmonization food legislation have all helped to a reduce the difficulties associated with shipping food products across international borders. As a result, the larger food manufacturers, at least, may have the option to locate their factory in one of a number of different countries. Several factors influence this choice, which may be far from simple. The principal ones are discussed in the paragraphs that follow.

11.2.1 Factors Influencing Selection

The following factors are likely to influence the selection of the factory site.

K.P. Sutton (✉)
Food Factory Design Ltd, 5 Bassetsbury Lane, High Wycombe, Buckinghamshire HP11 1QU, UK
e-mail: keithpatrick.sutton@btopenworld.com

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_11,

11.2.1.1 Proximity to Source of Raw Materials

A food factory must have ready access to an appropriate source of raw materials and ingredients. The following aspects need to be considered:

- Is the supply adequate and reliable?
- Are the raw materials of acceptable quality?
- Can the supply be purchased at an economically viable cost?

If the answer to any of these questions is “no,” then the proposed location is likely to be unacceptable.

It is often desirable, and in some cases essential, to locate the food factory close to the source of raw materials. Although this may be favored by economic and logistical considerations, quality issues may predominate. For example, fruit and vegetables destined for freezing should be frozen as soon as possible after harvesting; in the case of peas, a delay of only 3–4 h can result in the development of detectable off-flavors. The processing of fish, which begin to deteriorate immediately after they are caught, is an extreme case and has led to the widespread use of factory ships. Thus, frozen fish blocks, produced at sea, are now a common starting point for the manufacture of many of the standard fish products. The use of refrigerated transport provides increased flexibility in siting factories processing more tolerant products.

The transport of live animals over long distances prior to slaughter is the subject of a growing body of legislation, which may influence the location of meat processing plants.

Where the raw materials are not subject to rapid degradation, economic and other considerations will tend to predominate over quality issues. For example, provided that they have been predried after harvesting, where necessary, cereals can be transported over long distances without detriment. A flour mill can therefore serve a relatively large wheat-growing catchment area. In the brewing industry, water is an important ingredient. The distinctiveness of most premium quality beers can be attributed in part to the water composition in the area of manufacture since the activity and stability of enzymes involved in the mashing process are influenced by the inorganic ions in solution. As very large quantities of water are employed in this industry (typically six to eight times the volume of beer produced), tankering these volumes to a remote factory site would clearly be uneconomical.

Where raw materials are imported in bulk by sea, it is often advantageous to locate the manufacturing facility close to the port of entry. In many cases, the raw material can be conveyed directly from the ship to the factory.

Many raw materials consist predominately of water. In a number of cases, much of this can be removed prior to dispatch from the production site. This results in considerable transportation-cost savings. Examples include concentrated orange juice, milk powder, and tomato paste.

11.2.1.2 Proximity to Markets

Ideally, the factory site should be as close as possible to the envisaged markets or retail distribution centers so as to minimize transportation costs. In practice though, other factors enter the equation. In the case of products having a relatively short shelf life, such as bread, milk, and other dairy products, the factory tends to serve only “local” needs. However, progressive improvements in the transportation infrastructure (principally roads and vehicles) have enabled individual production sites to enlarge their customer bases. This, together with ongoing economic pressures, has led to the closure of many such facilities and to the consolidation of the remainder into larger, more efficient units.

Factories manufacturing products having a relatively long shelf-life tend to be large and to serve a much wider region. Thus, the production of a particular foodstuff required to meet national and, increasingly, international needs is frequently concentrated into a single factory. Any resulting increase in transportation costs is more than offset by avoiding the need to duplicate factory infrastructure, equipment and running costs.

The need to dispose of the inevitable factory waste, such as off-spec product for animal feed, should also be taken into account. Thus proximity to suitable farms is also an advantage.

11.2.1.3 Manpower Considerations

All food factories need access to a local labor force, which should have the range of skills required to run the factory. Consideration should be given to the terms and conditions of employment prevailing in the proposed locality. For example:

- Is the supply of workers having the required mix of skills readily available?
- Are wage rates and associated overhead costs excessive?
- Are there any prevailing restrictions on the number of hours worked per week?
- Are there any potential causes of labor dissatisfaction and/or high turnover rates? (For example, there may be a local employer, who, because of the nature of his business, is able to afford significantly higher wages.)
- Are any suitable training facilities available locally?
- Is the locality likely to be attractive to technical and managerial staff who may have to be relocated to the factory?
- If the factory is to be located in a remote area or developing country, what community facilities will have to be provided?

11.2.1.4 Availability of Utilities

All food factories require adequate and reliable supplies of water, electricity, and fuel (normally gas or fuel oil). It is therefore essential that the factory be located in an area in which these are readily available at an acceptable cost. In most cases, mains supplies of electricity, gas and water will be provided by the utility companies. Alternatively, in remote areas, it may be necessary to draw water from a local borehole, canal or river. In rare cases, it may be necessary to tanker it in. In this case, adequate storage must be provided. Electricity can be generated on site if needs be. This may be attractive if steam is also required, as the thermal efficiencies of CHP (combined heat and power) systems are generally quite high. Effluent disposal, including prior treatment on site, should also be given due consideration.

11.2.1.5 Transportation Infrastructure

Ready access to an efficient transportation infrastructure is an essential consideration in selecting a suitable factory site. Adequate provision must be made for the supply of ingredients, raw materials, fuel oil, etc., to the factory and for shipping finished product to the customer. In many cases, siting the factory within easy reach of a modern highway network can satisfy this requirement. Alternatively, it may be necessary to provide ready access to the railroad system, to a canal or other waterway, to a seaport or to an airport.

11.2.1.6 Financial, Legal, and Political Considerations

Business property taxation rates vary widely from country to country and even from state to state. There are similar variations in employment costs such as social security, unemployment insurance, redundancy payments, etc. Locating a new factory in a different country may also affect a company's liability for corporation tax. These factors should all be considered when making the selection. Conversely, certain locations may have been earmarked as development areas. In these cases, national and/or regional governments may provide generous incentives in the form of grants, loans, or tax relief in order to encourage companies to locate there.

Legal factors may also impact on site selection. Local regulations relating to zoning, building codes, nuisance aspects, possible future expansion, and transportation all need to considered. In order to avoid costly overruns, due allowance should be made in the construction schedule to overcome zoning difficulties and to obtain the required permits.

When considering the possibility of locating in a developing country, it is important to take a number of political considerations into account. The long-term stability of the country and its present form of government, in particular, should be thoroughly evaluated.

11.2.2 Making the Selection

As discussed above, the selection of the "best" geographic area in which to locate a new food factory is a complex and multifaceted problem. In many companies, it is tackled on a somewhat ad-hoc basis. More rigorous techniques, such as the Analytic Hierarchy Process (AHP) are now available, however, which may improve the quality of the decision-making process.

11.3 Is an Existing Facility Suitable?

In order to decide whether to use an existing facility, the following list of general requirements should be addressed, from which a reasonable judgment will evolve. In the event that the proposed facility does not currently provide all the necessary requirements, any remedial capital expenditure should be estimated. This can then be compared with the investment required for the "green-field" alternative.

11.3.1 Plan Size

Does the process layout fit within the confines of the building without compromise to plant efficiency? If not, what is the additional cost of extending the building (assuming that space is available), providing mezzanines or reducing equipment size? What is the likely cost in terms of a lower efficiency (more labor, more movement of materials?).

11.3.2 Height of Building/Stories

Is it sufficient to permit clear, unobstructed processing? If not, what is the cost of modifying the structure and/or roof?

11.3.3 Structural Integrity

Is the facility sufficiently well built to last the expected life of the process? Are the overhead structures/roof strong enough to support the required suspended plant, services, utilities, and ceiling systems?

Is the floor slab strong enough for the imposed loads and sufficiently durable? If not, estimate the cost to replace or strengthen it.

11.3.4 Internal Finishes

It is usually found that all floor, wall, and ceiling finishes and partition layouts require total replacement to suit the proposed production requirements and to meet current and increasingly stringent health and safety, etc., legislation. Alternative finishes are described in detail in Chap. 13. The cost of removal of existing finishes, etc., must be added to the refurbishment costs.

11.3.5 Main Utility Supplies

An existing facility will normally have mains supplies already laid on and the capacities of these can be checked against the proposed process requirements. However, due to the nature of constantly improving legal and hygiene standards, it is usually found that all distribution systems and sometimes even the main incoming control/metering systems do not conform with legal requirements. The cost of removal and new installation, therefore, tends to be higher than that of a green-field site, despite the presence of the main supply cables/pipes.

11.3.6 Services

Are there sufficient heat/steam raising, compressed air, water storage and treatment, cooling and air conditioning plants in the facility to provide the process requirements?

Again, it is usually found that existing systems do not comply with the legal standards or the client's hygiene requirements, and that total replacement or major upgrading is required.

11.3.7 Amenities

Are sufficient office, changing room, toilet, canteen, and welfare facilities available or, if not, what is the cost of providing them? Are external delivery and dispatch areas suitable? Is there sufficient parking for goods vehicles and staff?

11.3.8 Conclusion

As a rule of thumb, the cost saving achieved using an existing facility will generally be 25–30 % of the cost of a green-field factory. Against this must be placed the compromises that have to be made in terms of hygiene, layout, and efficiency compared with the ideal site.

11.4 Assessment of Green- and Brown-Field Sites

11.4.1 General

There are many factors to consider when choosing between a selection of possible sites within a local region (see, e.g., Schmidt 2011). It is recommended that a land surveyor be used to collect, check and collate all the relevant data before a decision to purchase any particular site is made.

A site assessment will normally be carried out in two stages. Firstly, a Desk Study will be undertaken, which will generally provide sufficient information to select from a choice of sites. This is followed by a Ground Investigation. A great deal of information can be found out about a site from existing records, maps, books, logs, etc., kept by local or national government departments and agencies or utilities suppliers.

The costs associated with a site assessment are minor in relation to the overall project cost, typically 0.5–2.0 %, and will pay for itself many times over by securing the most suitable site for both construction and production efficiency.

When a preferred site has been identified, a site examination and a ground investigation should be carried out, providing the owner is agreeable.

11.4.2 Site Desk Study

The following items, although not exhaustive, should form the basis of the study:

11.4.2.1 Planning

Contact the Local Government Planning Department and ascertain that the proposed development is acceptable in principle. If this is not the case, determine how it might be adjusted so as to comply with the “Local Development Plan.” It may be necessary to install, for example, effluent treatment facilities (see Chap. 18), to provide local enhancements, or to undertake land swaps, etc.

11.4.2.2 Constraints

Obtain information on local constraints of an environmental, conservation, industrial, residential or development nature (e.g., protected trees and sight lines, Sites of Special Scientific Interest, vulnerable watercourses, maximum noise emission levels, maximum development heights, rights of access, restrictive covenants, night working, etc.).

11.4.2.3 Situation in Relation to Other Industry

Study the surrounding neighbors (if any) and assess the amount of noise, dust, exhaust gases, odors, and taints that are emitted. Decide if any of these will adversely affect the proposed process or how they may be controlled by suitable filtration methods.

Determine whether any emissions from the proposed process will adversely affect the neighboring industrial, residential or rural areas.

11.4.2.4 General Land Survey

The following information should be obtained:

- A detailed map showing the exact location of the site, with all its boundaries clearly marked.
- The definition of any building lines to be complied with and the position of all structures, either on the site or surrounding the boundaries.
- Ground contours to ensure that ground preparation will not be extensive (most food processors prefer single-level layouts).
- Details of natural drainage features to ensure they can be protected or diverted without affecting the environment.
- Details of all above-ground obstructions, such as power cables, HV transmission lines or pylons, and telecoms cables.
- Details of all below-ground obstructions such as land drains, culverts, sewers, soakaways, and utilities supply mains.

Note that a significant cost may be incurred if it proves necessary to divert or protect any particularly large sewers or mains services.

11.4.2.5 Meteorological Information

The following meteorological data will provide useful information that can aid the detailed design of the facility in due course:

- Average minimum and maximum temperatures, monthly throughout the year
- Maximum daily rainfall
- Intensity of maximum rainfall (mm/h)
- Wind direction and speeds

This information will be similar throughout the immediate locality. It can be used to establish the best positions for dispatch/delivery canopies or shelters, air louvers, flue or exhaust air cowls, and waste bays. It will also influence selection of suitable roofing and cladding, requirements for surface runoff drainage, etc.

11.4.2.6 Ground Conditions

The basic information may be extracted from geological maps. Only in the second stage will a ground investigation be undertaken.

The following needs to be established:

- Is the site natural or made-up ground? If it is made-up ground, it is likely that piling, ground treatment or removal and replacement will be required adding up to 20 % to the building costs. Most natural ground conditions are suitable for food factories, as loads on the foundations are not generally high. Exceptions may be soft clays, silts, etc. Alternatively, if rock or rock outcrops are present, considerable effort and cost may be incurred in removing/reducing the rock or building up ground levels.
- Information on flooding, erosion, subsidence, and landslides. This is usually only obtainable from recorded memoirs or local knowledge. Central and local government may be able to assist.
- The results of investigations on adjacent sites. If available from neighbors, developers, or construction companies, these records may provide valuable information on the subsoil, water tables, etc.

11.4.2.7 Drainage and Sewerage

Obtain details from the local authority concerned and determine which bylaws apply to the proposed area.

Identify the position and levels of existing systems, with pipe sizes, and indicate if they are foul, storm-water, or combined drainage. Include ditches, drains, etc. If possible determine the existing flows and available capacities, which could be utilized by the proposed factory.

Identify if there is a flood risk from any of the drainage and sewer systems to the proposed factory or whether flooding might be caused elsewhere by the factory overloading the sewer.

The acceptability of additional effluent on the local sewer and sewage works must be determined by contacting the Trade Effluent Officer of the local water supply company. Comments relating to the acceptability or otherwise of the effluent should be obtained in writing for future reference. If the envisaged discharges exceed the permitted consent levels, it will be necessary to provide a suitable treatment plant to improve the quality of the effluent prior to discharging it to the public sewer or an appropriate water course. On-site treatment plants require Planning Permission and the likelihood of obtaining this should be established at the outset (see Chap. 18 for treatment methods).

Determine the local charges for the treatment of trade effluent discharged into the public sewer. These should include any capital contributions or income guarantees required for sewage works extensions. Significant additional discharges to a small treatment plant may necessitate major capital works by the water company.

Some effluents and the sludges arising from them may be suitable for land disposal, where land is available. This must only be carried out under careful supervision, with the written Consent of the Local Authorities and the Environment Agency (http://www.environment-agency.gov.uk/) or equivalent regulatory body. Note that the storage of effluent in lagoons also requires formal Consent.

Determine whether combination drainage is allowed or whether separate drains need to be provided for the various site discharges as follows:

Surface water drainage (roofs)	Direct to water course
Surface water drainage (roadways)	Direct to water course (via gasoline interceptor)
Surface water drainage (areas subject to contamination)	To sewer
Foul water	To sewer
Process water	To sewer

Where a formal Consent is required for a trade effluent discharge to sewer, a separate drainage system must be provided for this. It may combine with other drains only downstream of an agreed monitoring point.

It is not permissible to discharge any trade effluent or contaminated surface water to any sewer or water course without a written Consent, even where on-site treatment is provided. This includes cooling water, boiler- and cooling-tower blowdown water, and vehicle wash down. In the case of new developments, it also includes all rainwater drainage where this is to be discharged to a watercourse or soakaway.

Where there is no public sewer available, special arrangements will need to be made for effluent disposal, which may involve extensive on-site treatment prior to direct discharge to a watercourse. This should be discussed with the Environment Agency/Planning Authority at an early stage and an indication of likely consent levels and other requirements obtained in writing.

11.4.2.8 Solid Wastes

Food processing wastes are generally nontoxic but may be highly polluting due to their high biodegradability. Incorrect disposal could give rise to pollution or nuisance. Note that, in the present context, the term "solid waste" is taken to include semiliquid wastes that cannot be discharged to drain.

Proposed processing operations should be audited to assess the quantity and nature of waste that is likely to arise from their installation. This should include waste arising from routine processing and from servicing operations as well as that which might occur in exceptional circumstances, e.g., reject product that cannot be recovered or recycled in any way. Every opportunity should be taken to reduce waste by optimal selection of plant and process.

The following aspects relating to solid wastes should be considered:

1. Location of storage areas:
   Where waste quantities are more than minimal, it may be necessary to designate a specific area of the site for their reception and storage whilst disposal is arranged. This area should be as remote from production and storage areas as is possible but must not be sited where it could cause a nuisance. Access must be possible, both for site vehicles and for waste disposal contractors' vehicles. Particular consideration of these factors will be necessary where residential or amenity areas are close to the site. Proposals should be agreed with the Environmental Health Officer before they are formalized. Screening and/or covering of waste-holding areas may be required according to circumstances.
2. Drainage of storage areas:
   Drainage from waste-holding areas should normally be connected to the effluent system unless the written authorization of the Environment Agency is obtained for direct discharge to a watercourse. This is likely to be granted only where relatively inert waste is involved. In some situations it may be necessary to construct a low bund wall around waste storage areas to prevent the escape of spilled material or the ingress of storm water.

   Rodent control measures will also be required for waste areas and associated drainage.
3. Disposal routes:
   Proposed disposal routes for each type of waste should be identified at an early stage. It may be necessary to segregate certain wastes, e.g., those that could be sold for animal feed. Organizations that may be able to accept the waste should be contacted to provide an estimate of costs. All contractors should be able to provide evidence of holding licenses for the handling, treatment, and disposal of waste.
4. On-site disposal:
   Where there is sufficient land around the site, it may be possible to dispose of limited quantities of biodegradable waste by land spreading. This can only be done if the Local Authority grants a

waste disposal license. Disposal should not be attempted for wastes containing high levels of fat. Where such disposal takes place, local watercourses should be monitored regularly. It may also be necessary to monitor the quality of local groundwater.

Specialist advice should be sought where this means of disposal is to be considered.

5. Legislative aspects:
In the UK, provisions in the Environmental Protection Act (Regulations 1990) impart personal as well as corporate liability for the safe disposal of controlled waste. Waste from food-manufacturing sites falls within the definition of controlled waste. Similar legislation applies in many other jurisdictions. For example, in the USA, the management of hazardous waste is governed by the Resource Conservation and Recovery Act (RCRA), enacted in 1976, (EPA 2012a) and the Hazardous and Solid Waste Amendments to ERCA, enacted in 1984 (EPA 2012b). A producer of waste has a responsibility to see that it is disposed of properly and is labeled in such a way that this can be achieved. It means using a licensed disposal contractor and ensuring that the waste is being sent to a site which is licensed to receive waste of that composition.

Specific responsibilities include:

- Taking measures to prevent the escape of waste.
- Ensuring that waste is transferred only to an authorized person, as defined in the Environmental Protection Act.
- Ensuring that the transfer is accompanied by a written description of the waste.

An authorized person includes the holder of a waste management license. For further information on waste disposal in the UK, consult the Environment Agency (http://www.environment-agency.gov.uk/business/topics/waste/default.aspx).

It is possible that a waste management license will also be required to store wastes on site prior to disposal. It follows that early contact should be made with the waste regulation authority so that all requirements can be identified and costed.

11.4.2.9 Access to the Site

Check that road (or rail) access is achievable and sufficient for heavy goods vehicles without causing interference or nuisance to other road users or neighbors. Access aprons or roads will usually require approval of the Highways Department of the Local Authority whose prime consideration is safety. Early consultation is advisable, as they may demand that a specific access point be provided. This may then dictate site aprons and loading arrangements.

11.4.2.10 Mains Water Supply

Where a supply of water is required from the mains system, early contact should be made with the relevant water company.

Contact should be established after an assessment of total current and projected future volume and peak demand has been made. During the discussions, the following information must be obtained:

- The availability of the required volume of water at an adequate pressure. This should be sufficient to meet peak demands. Alternatively, it may dictate the need for on-site storage. In most cases, storage involving the use of a break tank will be required.
- Details of any capital contributions, infrastructure charges or similar that will be required by the water company to provide or up-rate a water supply and the timescale involved in carrying out any required works.

Details of the source, treatment, blending, distribution, and quality of the water supply, as detailed below, are also required.

- The source of the water should be determined, e.g., reservoir, lowland river, groundwater. The food manufacturer is particularly concerned with taste and odor problems. As a result, a water supply having a high and consistent standard of water quality is essential. Water emanating from lowland rivers and, in some cases, reservoirs are more likely to give rise to quality problems than groundwater. River water in particular is prone to considerable variation in quality. Groundwater sources should be more stable but any problems that are evident are likely to be of a long-term nature. Soft and potentially corrosive water is likely to be found in upland regions.

Any water used in food production must be suitable for purpose. If it is incorporated into the product or if it comes into contact with food or food-contact surfaces, it must be free of microbiological and chemical contamination. If there are any doubts, seek specialist advice. Quality issues relating to water use in food production have been discussed in ILSI (2008).

- Details of any water treatment carried out by the supply company should be obtained. Specifically:
  - Whether or not pre-chlorination is practiced.
  - The nature of chemicals used in the coagulation process, e.g., aluminum or iron salts.
  - Details of the use of activated carbon or other processes for the removal of organics, taste, odor, etc.
  - The nature of chemicals used for final disinfection.
  - Details of any pH, hardness, or alkalinity correction prior to distribution.
- Details of possible alternative supply sources or blending of sources should be obtained. Sudden changes in water quality may affect the product quality as well as any on-site water treatment plant.
- Details of the mains distribution system should also be obtained, in particular:
  - Problems with bursts, corrosion or scale.
  - Residence times of water within the system.
  - Any booster disinfection treatment.
- The quality of the water supply must be ascertained. This may be assessed by examining the water company’s last annual report and any subsequent analyses for the supply zone from which the water is to be taken. In the UK, the quality must comply with Tables A–E of the Water Supply (Water Quality) Regulations (Regulations 2000) and analyses must be available for all the listed parameters.

The Langelier Saturation Index (Wikipedia 2012; CSG 2012), or similar parameter, must be determined to give an assessment of the scale-forming or corrosion tendencies of the proposed supply. All relevant facts obtained should be considered by a specialist and a view should be taken regarding the following:

- The acceptability or otherwise of the supply for food-manufacturing purposes.
- Any on-site treatment and/or online monitoring that may be required.
- The requirement for water storage.
- The costs of providing any required treatment, storage, or monitoring of water, and any capital or infrastructure charges payable to the water supply company.
- The availability, suitability, and desirability of using alternative sources of water.

It should be noted that, even when a supply is wholesome and complies fully with the Water Quality Regulations, further treatment may be needed for specific processes, e.g., soft drinks production. It is almost certain that water will require treatment before use in boilers and it is mandatory that cooling water treatment be provided. Such additional treatment is the responsibility of the factory and not the water supply company.

11.4.2.11 Alternative Water Sources

In some situations, it may be appropriate to use a source of water other than the mains, e.g., a borehole, canal or river. The cost of water acquired from such sources may be much lower than that of mains water.

Where canal or river water is employed in food factories, its use should be restricted to low grade applications only, i.e., nonfood contact processes. Provision must still be made for disinfecting the water and, for this to be effective, filtration will usually be required. If there is any risk at all of this water contacting food, it must be treated in such a manner as to meet the requirement of the Water Quality Regulations. Even when the quality of the raw water abstracted from the river or canal does comply with this legislation, it is still desirable for it to be properly disinfected. In any event, this will be a requirement if the water is stored before use.

No water may be withdrawn from any source at any time until a license has been obtained from the appropriate authorities. In the UK, this is the Environment Agency and, in the case of a canal, the Canal & River Trust (http://www.canalrivertrust.org.uk). A check should be made to ensure that the conditions of the license are not likely to restrict the user's ability to withdraw in an unacceptable manner (e.g., seasonal restrictions).

A comprehensive analysis of any proposed source should be obtained or undertaken in accordance with Tables A–E of the Water Quality Regulations and, in the case of a surface source, account should be taken of any likely variations. Borehole samples should be taken after a period of pumping to ensure that a representative sample is obtained. It is recommended that a qualified hydrogeologist be consulted when assessing a borehole source.

A pollution risk assessment should be undertaken for any non-mains source of water. For other than very minor sources, this should be carried out by relevant specialists.

11.4.2.12 Gas Mains Supply

An assessment of gas requirements must be based on the peak demand of all the items of process and utilities plant. Whilst there is only a small likelihood that such a peak demand will occur, it could happen, for example, during a Monday morning start-up when the winter conditions are severe. Under such circumstances, considerable production losses may occur if the mains pressure and supply volume are insufficient.

Contact should then be made with the local gas company (or other approved contractor) to obtain the following information:

- The location, sizes and depths of mains.
- The type of gas, its thermal quality, and the pressure range available.
- If the existing mains supply is insufficient, the ability and cost (if any) to increase the capacity of the local mains.
- The cost of installing an incoming site mains supply, meter housing, meter, etc.

Appropriate arrangements can be made with any supply company to purchase gas at a competitive rate.

11.4.2.13 Electrical Mains Supply

An assessment of electrical requirements must be based on the demand loads of all process and utilities plant items. An assessment is usually made for diversification of load (e.g., phased start-up procedures) and specialist advice should be sought.

Contact should then be made with the local electricity company (or other approved contractor) to determine the following information:

- The location, capacity, and depth of the mains cables.
- The voltage, phases, and frequency.
- The capacity to supply the new requirements.
- Whether "ring main" or "spur" type provision is required for adequate protection of supply.
- Transformer plant and housing requirements.
- The cost of mains cables installation.

11.4.3 Site Inspections

When a desk study has indicated, in general, the suitability of a site, a detailed examination should be made. The adjacent ground should also be viewed to corroborate the desk study findings of neighboring use.

The site plan and geological map should be taken and the following information verified or additional information recorded:

- Set out the location of the building or check that it will adequately fit within the site boundaries.
- Observe and record omissions or differences pertaining to boundaries or buildings.
- Observe adjacent property and its condition and the likelihood of its being affected by the proposed works.
- Check and record details of any existing structures on the site.
- Observe and record all visible mains utilities or their likely routes.
- Observe and record water levels in ditches, streams, canals, ponds, etc., and the directions and rates of flow, where relevant.
- Compare surface topography with the map to check for the presence of fill, erosion or cuttings.

The following observations may indicate possible problems:

- Steps in the surface may be the result of faults, shatter zones, or mining subsidence.
- Broken and terraced ground on slopes may be due to landslips.
- Crater-like holes in chalk or limestone areas may be symptomatic of swallow holes filled with soft material.
- Flat areas in hilly country may be the sites of former lakes, characterized by soft peat or silts.

11.4.4 Ground Investigation

The desk study and site inspection should by now have established the suitability of the site. The ground investigation will provide details of the subsoil and related depths, and will provide the data necessary to design the foundations.

The principle elements of the investigation will provide information on the following:

- Is the site natural or made-up ground?
- Does the site or subsoil contain any toxic or harmful materials or any likely to cause tainting to foodstuffs?
- What is the likely depth of load-bearing ground? What is its safe bearing capacity, and what type of foundation system will provide the most economic solution?
- Whether uniform or differential settlement is likely to occur (e.g., in gravel soils)—its extent and possible duration.
- What is the natural water table level below the site? Is extraordinary drainage necessary (e.g., land drains to intercept surface runoff or subsurface movement)?
- What are the chemical characteristics of the soil? Are any extraordinary measures required to provide resistance within foundation structures?

All of the information obtained from the desk study, site inspection, and ground investigation should be passed on to the architect and/or lead designer. It is his professional responsibility to ensure the provision of appropriate and economic designs. He should also ensure that all aspects of the client's requirements have been addressed and provided at suitable cost or declined for a verified reason.

11.5 Closing Remarks

In conclusion, it has to be stated that site selection is a complex problem involving many factors, which should be properly considered and weighed. In many cases, the ultimate success, or lack of it, will depend to a significant extent on the correct choice of site.

References

CSG (2012) "Langelier saturation index calculator", CSGNetwork.Com, http://www.csgnetwork.com/langeliersicalc.html. Undated.

EPA (2012a) "Summary of the Resource Conservation and Recovery Act", U.S. Environmental Protection Agency, http://www.epa.gov/lawsregs/laws/rcra.html. Last updated 24 February 2012.

EPA (2012b) "Wastes—Laws and regulations", U.S. Environmental Protection Agency, http://www.epa.gov/waste/laws-regs/index.htm. Last updated 19 March 2012.

ILSI (2008) "Considering water quality for use in the food industry", International Life Sciences Institute (ILSI) Europe Environment and Health Task Force, Brussels, April, 45 pp. Available online at http://www.ilsi.org/Europe/Publications/R2008Con_H2O.pdf.

Regulations (1990) "Environmental Protection Act 1990". Available online at http://www.legislation.gov.uk/ukpga/1990/43/contents.

Regulations (2000) "The Water Supply (Water Quality) Regulations 2000". Available online at http://www.legislation.gov.uk/uksi/2000/3184/schedule/2/made.

Schmidt, H. "Determining equipment and process needs and how these affect food factory design", Chapter 2 in "Hygienic design of food factories", (eds) Holah, J. and Lelieveld, H.L.M., Woodhead Publishing, Cambridge, 2011, ISBN 978-1-84569-564-4, 784 pp.

Wikipedia (2012) "Hard water", http://en.wikipedia.org/wiki/Hard_water. Last updated 14 June 2012

Chapter 12
Design Principles

P.J. Wallin

12.1 Introduction

The design of a food factory is normally subject to many constraints, which can rarely all be met. It is essential that the design team is provided with a clear and adequate brief to serve as a point of reference. An outline of the contents of this brief is presented. In order to generate a range of potential solutions for subsequent evaluation, it is advantageous to produce a concept design based on this document. General design aspects (e.g. the architectural style of the building) and other critical issues are then considered as are the advantages of producing a preliminary design. Aspects of the site development plan are then described and the detailed design of the factory considered. Topics addressed in the latter include, for example, movement of materials and people, storage facilities, factory layout, and other features, including utilities and services. The chapter concludes with a brief discussion of environmental considerations.

Figure 12.1 illustrates the key phases of a project to build, extend, or redesign a food-manufacturing facility. This approach presents a simple methodology, which many companies have utilized and found to work. There are alternative approaches and each company has to select an approach with which it is comfortable, and which works best in its particular circumstances. Most food manufacturers do not design or build a new factory every year; hence, it is sensible to seek advice from people or companies that are involved in these activities on a regular basis. They will have learnt from previous mistakes and see opportunities for improvements. What the food manufacturer needs to develop is its own clear specific requirements and to be able to communicate these to the architect, designer, and builders so as to ensure their requirements are delivered. Within any project there are three constraints, as shown by the triangle in Fig. 12.2. These, which are frequently in tension with each other, are:

- Delivery on time
- Costs within budget
- Designed to specification (functions to requirement)

In a well-balanced project, the ball depicted in Fig. 12.2 should remain in the center of the triangle. The skill of the project manager is necessary to achieve this and to ensure that the project is totally successful. If only one or two of the above constraints are achieved, this will have financial repercussions either as a capital cost overrun, reduced revenues, or an ability to fulfil projected orders.

P.J. Wallin (✉)
Habwood Technical Solutions Ltd, Prestwood, Buckinghamshire HP16 9DS, UK
e-mail: peter@habwood.com

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_12,

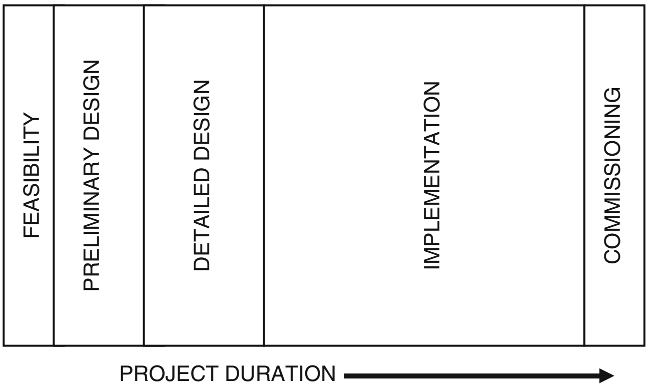


Fig. 12.1 Project phases

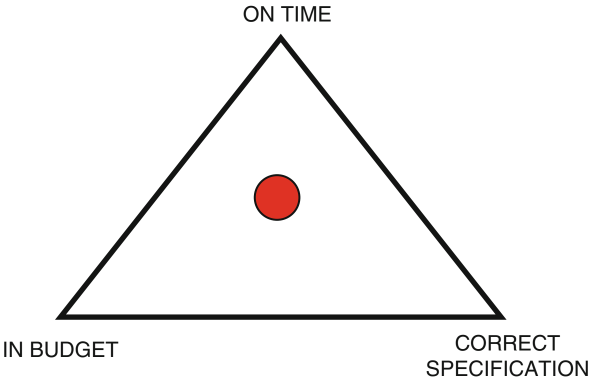


Fig. 12.2 Project constraints

12.1.1 The Brief

In order to design a well-planned facility, it is necessary to have an adequate and clear brief. This may be very basic and leave much of the details up to the architect and project engineer to develop, or it can be very detailed. In appropriate situations it could be a replica of the brief for an existing facility, modified as necessary. A brief should contain the following:

- Products to be produced in the facility
- Market and location(s) to be served
- Projected quantities and source(s) of raw materials
- Volumes of products required at start-up and preferably as a 5-year plan
- Ingredient lists, sample formulations, and likely product mix
- A brief process description (if this has been developed)
- Packaging requirements—types, sizes, and formats
- Future developments—second and third phases of expansion

The document will act as a point of reference for the design and construction team to work to. Without such a document it is likely that the design will not be optimal and there could be omissions or the design could be overcomplicated. The design brief is more critical to the success of the project than is usually thought. Although it is often difficult to tie the sales and marketing executives down to give both realistic and accurate data, it is most important that this information is available and is as accurate as possible. It will determine the size, shape, and complexity of the factory. These factors have a significant bearing on the capital cost but even more impact on the operating costs and the scope for future developments.

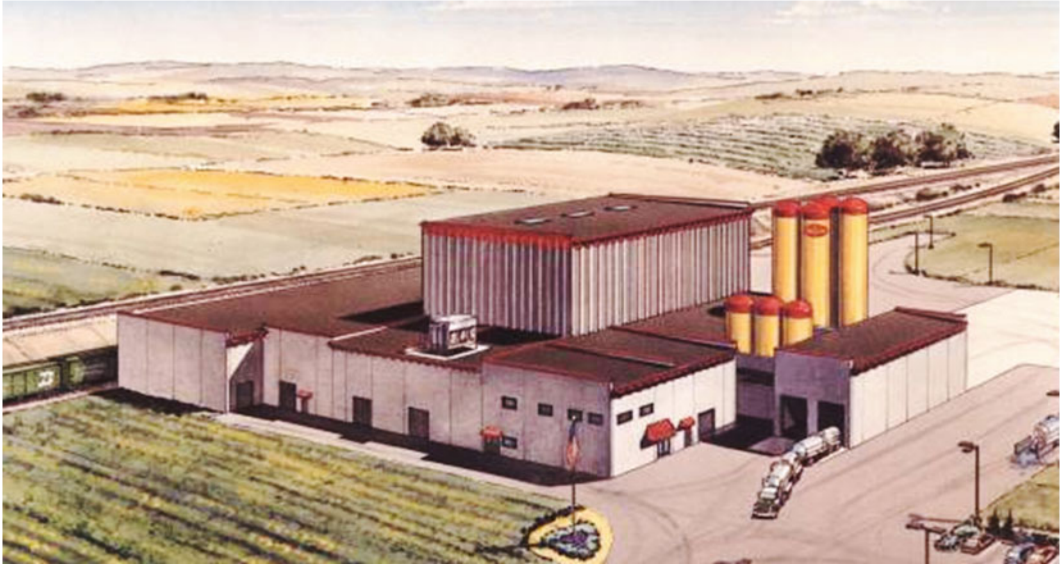


Fig. 12.3 Artist's impression of the exterior of a proposed food factory

If finance is required then it is normal for the investment bank or institution to request such a document, as it will want to know exactly what it is investing its money in. This is greatly assisted by a clear well-thought-out plan.

12.1.2 Concept Design

Before one develops an in-depth design, it is advantageous to carry out a design or concept study. This might take the form of a *factory of the future* type project or *ideal factory* study. It is not uncommon to employ consultants to undertake such a study. This allows a broader and deeper generation of ideas and potential options. Using an outside agency also allows one to be more creative and to stimulate ideas. The purpose of such a study is to generate a range of different potential solutions that can then be considered and evaluated to provide viable options.

The brief is used as a basis from which to develop the concept design. A concept design will normally contain some or all of the following:

- Artist's impressions (Fig. 12.3)
- Computer visualization and simulation—virtual reality model
- Layout options
- Benefits analysis and review
- Critical issues assessment

In the concept design it is worthwhile exploring how visitors and customers can effectively be catered for so they can view the factory without affecting production. The artist's impression, model, or virtual reality simulation will often be a little fanciful, but it is an important aid to communicate other possible concepts and to stimulate ideas.

In some countries these early documents are very important and have to be used to support the planning application or the permits required for the change of use of a building.

Fig. 12.4 Tilt-up concrete panels

12.1.3 General Design Aspects

The architectural style of the factory is significant and sometimes very important. Planning permission in certain locations is only granted if the building blends in with the local environment. It may be that the company wants to use the style to express itself and create a desired image for the organization. Below are some different styles:

- Low-cost functional, e.g., tilt-up concrete panels (Fig. 12.4)
- Durable long life, e.g., steel frame and brick (Fig. 12.5)
- Hoisted (raised) roof (Fig. 12.6)

The factory can be given a specific perspective, which creates a desired ambience such as a light feel, airy, spacious, or warm, rather than just basic and functional. The quality and type of building materials should also be considered. Although certain design features can add to the cost, the environment can induce higher levels of productivity, reduce sick leave, and retain staff.

Fig. 12.5 Steel frame and brick construction

Fig. 12.6 Raised-roof construction

12.1.4 Evaluation of Critical Issues

There are some specific aspects of the factory design or process that are critical to the company in order to make the factory a success. If these issues are identified up front, this helps to focus the project. Such issues could be:

- Specific raw materials or suppliers for a specific food or process
- Water quality—minerals, flavor, purity, etc.
- Skilled labor requirements

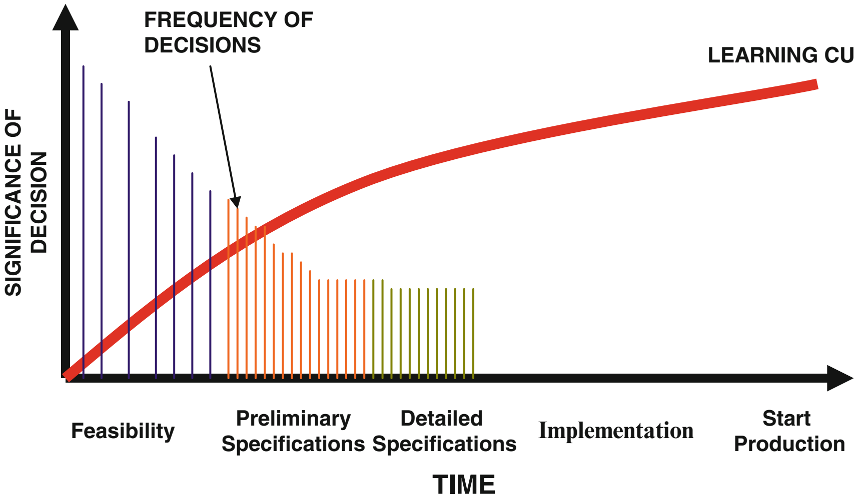


Fig. 12.7 Decision chart

- Visitors and auditors
- Parking and traffic

For a food company, the design of the factory is strategic and needs to be well thought through as it is a decision the company will have to live with for a long time—ten, twenty, or, in some cases, as many as 50 years. The critical issues will revolve around past experiences, the present shortcoming of existing facilities, future development of the company, and the personal experiences of the project team.

The issues will need to address the timescale for the project; if a fast-track approach is required, this will affect certain aspects of the facility's design. There may be opportunities to consider different building techniques, which enable the construction program to be accelerated.

12.1.5 Preliminary Design

The concept and ideas stages can take anything from a few days to several months, depending partly on how much time and money the company has available and/or the local authority requirements. Once these have been completed, the preliminary design can commence. The purpose of the preliminary design is to develop the selected concept into a more comprehensive plan and to evaluate it in more depth. This enables one to identify issues and avoid mistakes early on in the design process. Figure 12.7 shows a chart indicating the decisions that have to be made during the course of a project. The vertical lines represent the decisions and the height of the line indicates the level of significance. It shows that there are fewer decisions at the start of the project but they are much more important than those taken later; these are more numerous but less significant. It is therefore important to spend time and effort to ensure the early decisions are good ones, as they will have a major impact.

Building work can quite often be underestimated. Thus, anything to reduce the risk of delays and overspend is advantageous. The preliminary design phase is not always essential but is recommended and will reduce risk. Its objective is to develop and deliver the following:

- Site plan
- Basic layout
- Process specification
- Flow sheets

- Equipment specifications for major equipment
- Equipment list
- Utilities plan and requirements—steam, water, hot water, gas, electricity, freezers, chilled areas or rooms, and compressed air
- Cost estimate

12.2 Development of a Site

If a factory is to be built on a greenfield site, this can present many potential opportunities. These can be used to design a facility in such a way as to give the company a competitive advantage. The possibilities arising from a greenfield site are:

- Suitable location for distribution, logistics, and market.
- Proximity to raw materials required for production.
- Area in which labor costs are low.
- Utilities are available at competitive cost.
- Effluent and waste handling facilities are available.
- Areas or regions that provide attractive grants.
- Unsuitable neighbors (potential contamination, taints, etc.) can be avoided.

A good location is important, as it will impact significantly on the overall costs. If large quantities of raw materials are used and subsequently "concentrated" in the process, then considerable savings in transportation costs can be achieved if the processing facility is located near to the source of raw materials. Examples of this are sugar beet processing, slaughterhouses, meat processing, and vegetable freezing. For certain processes, it is necessary to source raw materials of a certain quality. A typical example is water for brewing beer or making soft drinks. In this case, the facility should be located adjacent to a suitable well, spring, or river. In most countries the cost of land is a significant factor, in particular for a small company, and therefore the facility may be located in a low-cost region or one that provides subsidies for new or developing companies.

Buildings are often viewed simply as a necessity to keep the wind and rain out. However, if designed correctly, the building space can be used effectively to assist in making the production facility more efficient and hence more profitable.

12.2.1 Overall Design and Layout

In order to create a good production area, one needs to consider some key aspects before starting on the detailed design. These are:

- Is the facility likely to expand in the next 5–10 years?
- How is the process or equipment likely to change?
- Is segregation of raw material, processing, or finished goods required?
- What are the key risk factors in the process?
- How much storage is required for raw materials, packaging, and semifinished and finished products?

It is important to understand the constraints and future flexibility required. Often the budget for the facility will force some constraints on the degree of flexibility that can be built into the design.

Company shareholders will not be happy if their money has been spent “just in case” something might happen; they need to be assured that their money is working to provide a good return.

Showing visitors around is a necessity in many factories and this requirement can be designed in. There are several ways to provide this facility. One possible way is to include high-level walkways, which can be both tidy and convenient and also used to route many of the utilities. They enable visitors to view all the operations without having to wear protective clothing and encroaching on the factory floor.

12.2.2 Access of Goods into and out of the Factory

The site design has to include provisions for the flow of goods into and out of the factory. Most ingredients and products arrive at and leave a factory by road and in some cases possibly by rail or sea. For transport by road, the accessibility for trucks needs to be considered. In some factories, daily truck movements can be appreciable, with more than one hundred movements. Therefore, parking, maneuvering, and turning of articulated vehicles, and possible disturbance to the neighbors, have to be borne in mind.

12.2.3 Number of Floors or Levels

The provision of two or more floors or levels in a factory can aid the logical flow of the process and also allow for the use of gravity to effect material flows. For certain processes, it is helpful to have a building with several floors so the materials can cascade down through them. In milling, for example, there are a number of processing steps, which can be separated onto different floors. With multilevel facilities, expansion can be hampered and costly if large and heavy equipment has to be installed on the higher-level floors.

Using a multistory design can have some other advantages, particularly where one wishes or needs to segregate different materials. Using different floors for different stages in the process can provide an excellent barrier. Factories often use a floor for handling semifinished or finished products, so as to prevent contamination from dirty or unprocessed raw materials.

It is preferable to locate all the packaging lines on one floor, although any filling or packaging materials could be conveyed or fed from a floor above or from a mezzanine level.

12.2.4 Size of Facility

A factory is nearly always too small after it has been built; therefore, it can rarely be too large. The size is usually limited by the budget or the size of an existing building. In considering the size of a factory, one should take the following into account:

- Access requirements
- People
- Fork lift trucks
- Maintenance
- New equipment installation
- The storage of raw materials near to processing equipment

- Requirements for packaging materials close to packaging machines
- Work in progress—when appropriate

In order to calculate the necessary size for the factory, it is worthwhile developing a proposed layout and arranging cutouts of the main equipment on it. It is also now possible to use virtual reality and advanced 3D modeling to design a factory. This allows one to check whether there is sufficient space and evaluate different options. The models can allow one to look at different views of the layout.

12.2.5 Type of Site

The site selection is an important decision to be made in the process of designing and building a factory. It is a decision that needs some time and consideration. There are companies that specialize in site search and selection and they will take this task on for a company.

12.2.5.1 Greenfield

A greenfield site, as the name suggests, is one that has not been built on previously. In many countries it is now difficult, if not impossible, to find a greenfield site on which to construct a factory. A particular area of land may be designated for factories (Industrial Zone) and sometimes specifically for food factories (Food Park). If one can find a greenfield site on which to build, this normally simplifies the design process and allows the architect more scope and fewer constraints. However, there are some drawbacks with a greenfield site; for example, the level of infrastructure required is normally high due to aspects such as:

- Drains.
- Access roads.
- Electrical supply and substation.
- Gas pipelines and pressure-reducing stations.
- Telecommunications.
- Time for planning approval.
- Overall time to build—in inclement locations, building works may be impossible for several months of the year.

12.2.5.2 Brownfield

A brownfield site is one that was previously used for another purpose. Typically, the new factory will be built on the site of an existing building, which will be either demolished entirely or revamped to meet the new requirements. This type of site is becoming more common due to the reduction in the availability of greenfield sites. Naturally, the brownfield site has to be evaluated fully. The following key points should be considered:

- History of the land and previous uses (e.g., burial, landfill). This information is usually available from local records.
- Any previous contamination of the land?
- Effluent disposal and treatment.
- Utilities—sufficient for requirements?

With some food products it is important to ensure that there are no likely odors that can be released from the site due to previous uses as this may flavor or taint any food products produced there.

12.2.5.3 Existing Facility

One fast-track route to establish a food factory is to reuse an existing building. Doing so will reduce considerably the lead time relating to planning and construction. There are naturally advantages and disadvantages to this approach. The advantages are:

- Lower investment cost.
- Older buildings are often built better and last longer.
- Planning permission is not required (unless major building works are necessary).
- Only permission for the change of purpose of the building will be required.

Some of the disadvantages are:

- Building may not be of an ideal shape or size.
- Roof may not be of optimum height.
- Drains and a wastewater treatment plant may need to be installed.
- Air handling/HVAC systems could need upgrading.
- Floors, walls, and ceilings could need upgrading to a hygienic finish.

The existing facility will have to be checked to ensure:

- The structure is sound.
- The roof is in good condition and there are no leaks.
- The building and grounds are not contaminated in any way.
- Effluent systems are appropriate.
- Drainage is suitable.
- There are no restrictive covenants or deeds on the land or existing factory.

12.2.6 Site Survey

It is essential that, once a site has been selected, a full survey be carried out. It is important to know the underlying soil conditions. If one is to construct a new building, soil samples will determine the foundation requirements and the amount of work that will be required to dig foundations or install suitable piles. The soil sample should also be analyzed to check for possible past contamination of the land.

The site survey and research should help discover the level of the water table, which determines the likelihood of flooding. It is also necessary to investigate the likely pests that may surround the factory as some areas of the countryside or town can present significant pest and infestation problems. Proximity to woods, rivers, or canals can provide a habitat for pests.

The survey will also need to check whether any restrictions have been imposed on the site such as noise levels and hours of working.

12.3 Fundamental Design

12.3.1 Movement of Materials

A variety of materials have to be moved through the factory: product progressing through the stages of production, ingredients being transported to their point of use, or packaging materials being supplied to the production line. The movement of these materials is critical to manufacturing and in making the factory run efficiently. The location of the materials is vital to ensure good performance. If the packaging materials are stored a long way from the packaging lines and on the wrong side of the factory, every trip to replenish the supply will take longer and the truck or conveying system will have to be accommodated.

One simple method of analyzing the flow of different materials to discover if any bottlenecks will exist is to use a proposed factory layout drawing and mark on it, in a different color for each material, its path through the factory. This method quickly highlights where there is a lot of movement as there will be a high density of different colored lines. A more sophisticated method is to use computer simulation tools, which can show the movements graphically. On many systems this can also be shown in three dimensions.

12.3.2 Movement of People

Unless serious attention is given to the movement of people through or into and out of the factory, this can adversely affect performance. In many cases, however, this is often only considered as an afterthought. Although as humans we think we are clean, people are actually the greatest cause of contamination in a factory. They can, for example, harbor dirt, dust, and disease on their clothing, hair, hands, etc.

If the factory has a large number of staff and operates a shift system, it is important to consider what is likely to happen during shift changeovers. The following questions should be answered:

- How many people will be moving in and out in a certain time window?
- Are the corridors large enough?
- Are the locker rooms suitable?
- Are cleaning facilities adequate?

Depending on the products produced in the facility, there will be a need for personal sanitation. This may include:

- Changes of clothing (sometimes including boots or overshoes)
- Hair net and hat
- Hand wash and sometimes sterilant wash
- Foot wash (mainly for meat processing and wet facilities)

12.3.3 Modeling of Flows

Modeling can help evaluate whether the best design has been selected and whether it is workable. Now that modeling can be carried out quickly and at a low cost, it is not just a luxury but an effective tool. Three-dimensional modeling with good rendering allows one to view the potential design in a realistic form.

12.4 Materials Handling and Storage

12.4.1 Raw Material Storage

The storage of raw materials is important in order to ensure that there is an adequate supply to keep the production running. In some situations it is possible to operate a just-in-time (JIT) system with suppliers. The JIT approach allows the manufacturer to limit the amount of on-site storage of materials knowing that he can call upon the supplier to deliver within a prearranged timescale; often this is within hours or even minutes. Some of the issues to be considered when designing a raw materials storage area are:

- Size of storage facility
- Type and size in which ingredients are delivered—bulk, sacks, bags, etc.
- Handling of materials—flow characteristics
- Effect of ambient conditions on ingredient
- Materials of construction of the store
- Whether full pallets and racking can be considered
- Life and stability of ingredients
- Health and safety implications—fire, explosions, etc.
- Infestations, cleaning, and hygiene
- Inventory control—first in first out?

Usually one would consider four types of storage conditions that could be required, depending on the particular ingredient or packaging material. These are:

- Ambient
- Ambient—air conditioned or humidity controlled
- Chilled (0–10 °C)
- Frozen (-10 to -40 °C)

For each of the above, the size of store required would need to be calculated based on the storage requirements. These will relate to the usage of each material, the minimum stock level to be held, and the shelf life of the ingredient.

12.4.1.1 Bulk Storage

Bulk materials received, whether delivered as complete pallet loads, in tipper trucks or in tankers, should be stored under appropriate conditions for that ingredient. Some protection may be required to prevent the ingredient from freezing or being exposed to rain, high temperatures, and humidity. If it is packaging materials, such as cases, cardboard cartons, or laminated card, then it is likely to require specific storage conditions so as to prevent moisture changes, which then affect how it performs on the packaging machine(s).

12.4.1.2 Flowable Materials

If large quantities of specific raw materials are to be used in the production process, these are normally delivered in the largest batch size possible. This is usually a tanker or lorry load of 20–50 t; in some countries this can be slightly higher. Storage capacity is required for a full load so as to minimize the transportation costs. A silo should therefore be sized 20–30 % larger than the maximum truck capacity. Flowable materials include liquids, powders and some solids, e.g., oils, melted chocolate, and milk; or solids such as salt, sugar, flour, proteins, fruit, grains, and vegetables.

Storage for these materials is usually in large silos or tanks. The ingredient is pumped or blown directly from the tanker into the storage vessel. Pumping or blowing is a quick and convenient low-cost method of transfer. The design of the silos and transfer system are important. Some key elements to consider are:

- Size—should be sufficient to receive more than a full load.
- Foundations—sufficient for point loading.
- Planning permission may be required, particularly if they are at high level.
- Access for delivery of materials to the silos must be adequate (narrow roads, cables, etc.).
- Material properties—will they flow or compact?
- Tanker access and suitable docking area.
- Blowers or pumps should be sized correctly for pressure and transfer rates.
- With blowers there must be adequate air handling and noise protection.
- Provision for cleaning of silos and inlet/outlet pipework.

In order to account accurately for the materials being delivered to the factory and to check the weight of the truckload, a weighbridge is essential. The weighbridge should be located conveniently and is normally sunken into the road so that the mechanism is hidden and protected. The weighing platform is then flush with the road. Alternative systems employ a raised platform with a small ramp to drive up on. This saves having to dig a pit and is more suitable where there is a high water table. The lorry drives onto the weighbridge and is weighed prior to delivering ingredients or materials. It is reweighed after the delivery has been completed and the difference in weight recorded as the amount delivered.

12.4.1.3 Other Materials

Raw materials that do not flow, materials used in smaller quantities, or ingredients having a short shelf life are usually transported in sacks or containers on pallets. The pallet is a convenient method for transporting materials as it allows easy transfer of the materials by forklift truck for loading and unloading. Most pallet loads will weigh around 1 t depending on the bulk density of materials stacked on it. A fully loaded pallet is usually between 1 and 3 m high. The height is limited by the stability of the stack, its weight, and the height clearance of the truck transporting it. Full pallets would normally be stored in the warehouse on racking. The warehouse operating conditions are designed according to the nature or requirements of the ingredients. The three most common conditions are chilled (4–10 °C), frozen (−10 to −40 °C), or ambient (20–25 °C). Pallets can either be stacked on top of each other, normally only 2–3 high, depending on stability or safety factors, or, preferably, they can be placed in a racking system, which will often accommodate up to 6 pallets high. When stacking full pallets on top of each other, one has to make sure that the material on the pallet below will not be compressed and damaged. The number of pallets that can be stacked on top of each other will therefore be product dependent.

12.4.1.4 Packaging Materials

Packaging materials are an essential part of any factory. Their storage and handling within the factory are often underestimated and poorly designed. In many factories one can observe packaging material obstructing walkways and affecting the general flow of people and other materials or products within the factory.

Fig. 12.8 High-bay warehouse

It is worthwhile studying the flow and likely use of packaging materials throughout the factory. Good positioning of local packaging material stores is essential. Storing material on a floor above the packaging floor can be a good concept, which then allows them to be fed from above to the point of use. This approach separates the materials from the machine area, keeping it clean and easier to manage. It also allows the packaging materials to be kept at different humidity and temperature conditions, which is important with many paper- and card-based materials, since it will improve the efficiency and general performance of the packaging machines.

Packaging materials are expensive. Therefore the system specified to store and convey them should be designed to prevent or at least minimize damage.

12.4.2 Finished Goods Storage

Once the final product has been produced, it has to be stored somewhere. Up until a couple of decades ago, the normal practice was to store products at the factory to await shipment to the customer or to a warehouse. Now it is normal to store finished goods on site for the minimum possible time and to ship them as soon as possible to a warehouse, which is often located locally. Specialist logistics companies, rather than the food manufacturer, frequently operate these external warehouses, which are often of the high-bay type. Here racking is used to stack pallets up to 12-high (Fig. 12.8), which makes the best use of space and provides a low-cost solution as the racking acts as the building structure. The reasoning behind this is that, although the food company has the necessary expertise at adding value by converting raw materials into product, it may not necessarily have the particular skills or facilities required to store and ship products.

The design of the finished goods area, where the product is prepared for dispatch and shipment, must be well thought through; otherwise, considerable product damage can occur. A few aspects to be considered are:

- Dispatch docks—good design making it easy for trucks to locate onto and at the best level.
- Dock leveling systems or maybe ramps required.

- Necessary space for forklift trucks to operate in.
- Climatic conditions—ensure that the product does not receive a temperature shock moving into a cold or hot truck. This is particularly important for ice cream and baked products.

12.4.3 Production Area

The layout and design of the production area is closely related to the nature and function of the equipment to be housed in the area and the sensitivity of the product. Different food facilities will have different requirements. Often there is a key piece of equipment, which has to be located correctly to ensure that it is possible to operate effectively and efficiently. Examples of such equipment include:

- An extruder or an oven
- Pasteurizer or sterilizer
- Continuous freezer
- Dryer
- Coating and frying system
- Filling machine

The first question regarding the processing area is—should it be wet or dry? This will obviously depend on the product and process. A liquid-processing facility (breweries, dairies, drinks, etc.) tends to be wet as a lot of washing down is required. However, with improved cleaning- and sterilization-in-place (CIP and SIP), some companies have favored moving to a totally enclosed processing system. For dry processes, such as baking and cereals, the facility will be dry with a minimum amount of water used in cleaning. It is always best to segregate physically the wet and dry areas and to provide adequate drainage in the wet area. For further guidelines on the construction of floors, see CCFRA (1993).

12.4.4 Ingredient Preparation Areas

The ingredient preparation areas are essentially areas where raw materials are handled and prepared prior to be being cooked, baked, frozen, etc. The area will have good drainage to allow adequate cleaning. The floor needs to be sloped to allow cleaning water to drain efficiently and quickly. The design of the area needs to be open and light to allow any dirt or debris to be easily visible. The building materials need to be robust and durable so as to withstand heavy-duty cleaning.

The design of the walls and floors needs to be such as to have no dead areas. Finishes should be smooth so as to stop dirt accumulating and to allow easy cleaning. The finish of the walls and floors needs to be of a suitable material (epoxy, tiles, etc.), which will resist acid and alkaline used in cleaning. Any grouting or mortar used needs to be of food grade and acid resistant.

12.4.5 Clean Area

The cleanest area of the factory is where the processing, filling, or packaging takes place. The ingredients are prepared in the ingredient handling area and then fed through to the clean processing area. A "clean area" is generally referred to as an area where food has already been heat-treated or preprocessed. This area is where the food is most vulnerable to microorganisms and contamination. A HACCP study will establish which areas are subject to the highest risk and will identify the critical control points. One of these usually occurs when the product has been processed and changes from the unprocessed to the processed form. It is advantageous to design the factory in such a manner that the ingredient preparation, unprocessed (dirty), and clean (processed) areas are separated by walls.

HACCP, the hygienic design and operation of food-processing equipment, and related topics have been widely discussed in the literature. Some useful references include Holah and Lelieveld (2011), IFST (2007), Imholte (1984), Jowitt (1980), Lelieveld et al. (2003, 2005), Marriott and Gravani (2006), Mortimore and Wallace (2000), Sprenger (2009), Stranks (1995), and Wallin and Haycock (1998).

12.4.6 High-Risk Area

In some cases it is necessary to partition the factory into low- and high-risk areas. This allows greater control of the movement of:

- People
- Air
- Ingredients and products

The principal reasons for providing a high-risk area are as follows:

- The product is microbiologically sensitive.
- It is not naturally stable.
- There is no “kill” step—fresh products with no processing.
- Contamination from other areas of the process or from the raw materials is possible.

The typical types of facility, which present a higher than normal risk, are:

- Production of ready meals—sandwiches, salads, etc.
- Baby foods
- Cooked meats and pies—often eaten cold
- Sauces and condiments, which will not be reheated
- Flavors and spices

Depending on the potential risks, there are a number of actions one can take to improve the cleanliness of an area:

- Staff change into clean clothes to enter high-risk area.
- Clothes are more protective (single use before cleaning)—footwear is changed.
- Walls are designed for full clean down.
- Floors can be easily scrubbed and drains can be cleaned.
- Equipment can be foamed down.
- Fogging can be used in extreme cases.
- A high positive air pressure is used in the room.

For further information on air quality standards in the food industry, see CCFRA (1996) and for HVAC design, Haines and Wilson (2003).

Table 12.1 American classifications for clean rooms

Class name	0.1 μm	0.2 μm	0.3 μm	0.5 μm	5 μm
1 (M 1.5)	35	7.5	3	1	N/A
10 (M 2.5)	350	75	30	10	N/A
100 (M 3.5)	N/A	750	300	100	N/A
1,000 (M 4.5)	N/A	N/A	N/A	1,000	7
10,000 (M 5.5)	N/A	N/A	N/A	10,000	70
100,000 (M 6.5)	N/A	N/A	N/A	100,000	700

12.4.7 Sterile (Clean) Rooms

For certain processes, it is necessary to use a sterile or clean room in which the atmosphere is free of contaminants. This is only likely to be necessary when one is handling very dangerous or hazardous materials, very sensitive ingredients, or sensitive foods. Air and people are two of the most important aspects to control. Air entering clean rooms is filtered, commonly using a HEPA filter. This removes dust, microorganisms, molds, fungi, etc., from the air, thereby only allowing “clean” air to enter the building. HEPA filters require a high level of maintenance and need to be changed regularly as they collect a lot of dirt. It is therefore important to install the filters in an accessible location.

Clean rooms can be graded according to the level of dust/material allowed into the room and the natural shedding of materials. The American classification for clean rooms is summarized in Table 12.1, which shows the number of particles allowable per cubic foot of air (American Federal Standard 1992).

In the clean room it is also important to control the access of people and the materials as they can easily contaminate the room with, for example, hair, flakes of skin, and saliva. People have to be dressed in suitable clothing, which is clean and decontaminated, and is also non-shedding. Materials entering the clean room are normally transferred into washable containers or cleanable plastic pallets. The containers should be specifically colored to show that they should be used solely in the clean room.

12.4.8 Packaging Area

After the product has been processed and sealed into its primary container or pack (can, bottle, jar, or plastic pot), it is often packed into secondary packaging (shrink wrap, case, basket, bag, crate, or carton). After the secondary pack there is often a tertiary pack, usually consisting of a cardboard case or plastic shrink wrap. This pack is then palletized.

In many factories, packaging is quite complex and is frequently more sophisticated and more complicated than the process. Hence, the packaging area is generally the larger and more dominant part of the factory. A good packaging area should:

- Be well laid out—preferably in straight lines and having good access
- In most cases, be flexible
- Be efficient
- Exhibit high productivity
- Exhibit a high utilization factor and quick changeovers

The best type of building to house the packaging lines is one that is open with no roof-support columns. A long building is normally better than a short one; otherwise, the packaging lines will have to double back on themselves. A good straight-line packaging concept allows operators to see product flow clearly and to identify problems quickly. A lack of bends or turns in the lines reduces complexity and potential problems, such as product falling from the conveyor and excessive wear on conveyor systems. It is also important for a packaging area to be extendable as over time packaging systems change and more lines are likely to be added. It is good idea to look at the overall packaging area and plan how the building could be extended to accommodate future changes.

12.5 Detailed Layout of the Factory

12.5.1 Factory Design

In order to develop the preliminary specification for the factory into a more detailed design, it is advisable to break the work down into different areas—floors, process, etc. For each area it is important that the detailed design is able to provide answers to the following questions:

- Will the equipment fit into the building?
- Is there sufficient space around equipment for operation, maintenance?
- Is the floor strong enough—calculation of point loads?
- Is it a wet or dry area and how will it be cleaned?
- Is there sufficient power for all the equipment?
- Are the utilities (water, gas, etc.) sufficient?

12.5.2 Process Specifications

The process is the heart of a food-manufacturing operation and it has to be efficient and well designed. There are major differences in the design of factories for different processes. It is therefore difficult to generalize and cover all possibilities. However, Bartholomew (1987) describes in some detail the process flow sheets and specifications for the manufacture of a number of food products. Some important principles set out below should be followed:

- Develop a simple block diagram of the process including all capacity information.
- Draw out flow sheets—include flow rates and process and utilities capacity information on the drawing to avoid errors.
- Develop a dimensioned layout to be sure that the equipment will fit properly and that there are no clashes with the building or other equipment.
- Prepare an equipment schedule itemizing each major item. This can be in the form of a database or spreadsheet and also used for cost estimates as well as technical information.

12.5.3 Equipment Specifications

In order to develop the detailed design and specifications for each of the areas, the use of a project management company can help significantly. It needs to be given clear instruction, a clear scope of work, and a suitable contract. Many companies use equipment suppliers to develop these specifications as they have more knowledge and often have standard specifications they can apply for particular processes. This phase is time consuming but must be carried out diligently with particular attention to detail.

12.6 Other Facilities

The factory's main purpose is as a production facility and that is what produces profits for the company. In addition to this, there are also a number of other functions that will need to be included within the factory. It is important to consider each of these in the total scheme rather than as an afterthought as the integration of all the necessary departments and functions will determine the overall efficiency and effective running of the factory. The following sections consider some of these.

12.6.1 Office Design

The design of the office space needs to be conducive to office work. Open-plan offices are often advantageous as they can make better use of the space and communications can be simple and effective. The design of the offices for a factory is frequently left until last and therefore commonly ends up as an afterthought.

In considering the offices it is necessary to think through the following:

- Size
- Access
- Computers and utilities cabling and networking
- Cloakroom, restroom, and washrooms
- Working environment
- Artificial and natural lighting
- Windows
- Heat—winter and summer

Some factories have designed the offices with a little more architectural flare than the rest of the building. This can make the factory more attractive, help with planning permission, and affect people's impression of the company.

12.6.2 Amenities

Associated with any building are the staff who are to operate the facility. Many companies now set certain standards for their staff regarding the amenities they should have access to. Some of the more obvious ones are:

- Lockers and changing facilities
- Toilets and washroom facilities
- Eating area
- Vending machines or canteen
- Smoking room
- Parking and bicycle racks

The above are often a legal obligation in many countries. One needs to check with the local requirements, which will be available from the local planning authority. The number of toilets required is obviously determined by the number of employees and by the split between males and

Fig. 12.9 Landscaped factory

females. One will also need to allow for visitors; for some companies the number can be significant. Toilets and washing facilities will need to be located strategically for convenience and hygiene.

The dining facilities should be pleasant and allow the staff a period of rest. It is important that the decorations, lighting, sound levels, etc., are appropriate and interior designers can be used to achieve the correct ambience. One will require some space to provide for relaxation but not too much that it means staff are not motivated to return to work again after the break.

Some of the specific facilities companies may wish to provide are:

- Team rooms
- Staff shop
- Games area—darts, pool, etc.
- Exercise room
- Coffee area

The size of the facilities will again have to reflect the number of employees. The layout and location of the staff facilities is important to ensure that the site segregation is not affected (high- and low-risk areas, "dirty" and clean areas). In some circumstances it may be necessary to duplicate facilities. A separate area will need to be created for smokers, which is equipped with good ventilation to prevent smoke entering other areas. Many companies have a social club attached to the factory, which arranges sports events and other activities.

Care and attention to the landscaping of the site (Fig. 12.9) creates a good impression with visitors and enhances the image of the company. It also provides a pleasant working environment for the employees.

12.6.3 Laboratory and Quality Inspection

For most manufacturing facilitates there is a requirement to test materials, ingredients, finished products, or other chemicals used in the manufacturing process. The laboratory can also have a microbiological section for testing hygiene levels. It is therefore necessary to have a facility where materials can be taken to and tested. Because analytical equipment is often fragile and analyses complex, the equipment is likely to be housed at a separate location.

Some of the key design aspects of the laboratory are:

- Location of fume extraction systems
- Design of stack/vents from fume cupboards
- Emergency exits—particularly if hazardous chemicals are used
- Storage of gases or other hazardous materials used for analyses

The fume extraction system needs to be correctly placed on the roof to prevent emissions from entering the factory's air intake system. The exhausts are best located downwind of the factory so they are immediately carried away and diluted. The exhaust stack needs to be of sufficient height to ensure that the discharge is dispersed.

Depending on the process, it may be necessary to carry out analyses "at line" (i.e., next to the processing equipment) as the results may be needed to control the process or the sample being analyzed may change rapidly over a short time. In this case, a small test room or a hood over the equipment is usually sufficient to protect the equipment and provide an effective facility.

12.6.4 Maintenance and Engineering

Proper maintenance is key to the efficient running of the factory. In order to have effective maintenance, whether it is planned, preventative, or reactive, one needs to have the correct and most efficient facilities. Most factories will require a workshop where quick repairs can be made and some overhauling of equipment carried out. The space required for such a workshop will vary according to the size of factory and the type of processes involved. The workshop will need to be:

- Close to the factory floor so as to enable repairs to be carried out quickly
- Adequately sized so people can work efficiently and effectively
- Effectively lit and heated
- Equipped with the correct tools and facilities to suit the envisaged tasks and aid efficiency and quality of the work

The workshop will need good lighting. Where intricate work is to be carried out, 500–600 lux is recommended (Stranks 1995).

12.6.5 Control Rooms

Automation is an increasingly common feature of the modern food factory. There is therefore an ongoing requirement for process and production controls. Views differ about how best one can implement and incorporate automation. Some companies prefer a large centralized control room from which all operations within the factory can be controlled and directed. Others prefer a distributed approach to control with decisions being made locally by the operators. A distributed system is advantageous if a large number of manual tasks need to be performed.

The control room should have its own HVAC system to ensure that any computers are adequately cooled and do not overheat and to prevent a buildup of dust. If operators are to be based in the control room, air conditioning also provides an environment, which can aid productivity and effectiveness. The room will need to be of sufficient size for efficient working. It is advantageous to have plenty of windows in the control room to enable the factory operations to be viewed easily.

12.6.6 Electrical Switch Rooms/MCCs

Modern highly mechanized food factories contain many items of process equipment and, therefore, require a good electrical distribution system to supply the necessary power to the machines. Starters for major items of equipment can be housed in motor control center (MCC) panels. A site will receive a high-voltage power supply from the local electricity company. This is fed to a transformer, which converts it to a three-phase supply at a lower voltage.

The main power distribution board(s) is best located near to the main power users in the factory. Doing so will reduce both the power loss and electricity costs.

Both the transformer and the distribution system should be located in a protected area in order to minimize safety risks and the possibility of fire if any shorting out occurs. It is usual to house the main starters and switchgear in a self-contained area. The room should be equipped with an automatic Halon (or similar inert gas) fire-prevention system.

12.6.7 Compressed Air

An adequate supply of compressed air is required within the food factory to meet a variety of process needs such as the conveying of powders; mixing of granular ingredients; aeration of liquid foodstuffs; drying, opening, and closing of valves; and the operation of packaging machines. The supply is generated by means of a suitably specified and sized compressor; a typical selection chart is given in Peters et al. (2003). Centrifugal compressors are widely used to meet high-capacity requirements (>10,000 m^3/h at inlet conditions) and have the advantage of being oil-free by design. At lower flows, rotary screw or reciprocating compressors may be employed. Depending on the design, these may be oil-free or lubricated.

In many processing operations, compressed air is in either direct or indirect contact with food. In such situations, which will be identified via a HACCP analysis, it is necessary to prevent contamination of the product as this can give rise to color and taste changes, reduced shelf life, and exposure to microorganisms. The principal contaminants that may be present in compressed air include particulates, water (vapor and liquid), and oil (aerosol liquid and vapor). All three are found to a greater or lesser extent in ambient air. However, additional contamination may result from rust and scale particles in the ductwork, condensate produced as a result of compressing the air, and oil leakage through worn seals, orifices, and o-rings in lubricated compressors. As discussed below, it is therefore necessary to treat the compressed air prior to use to reduce the contamination levels to acceptable values.

ISO 8573-1 (ISO 2010) specifies purity classes of compressed air with respect to particles, water, and oil independent of the location in the compressed air system at which the air is specified or measured. It also provides general information about contaminants in compressed air systems and identifies gaseous and microbiological contaminants. Parts 2–9 of the standard describe the test methods employed to accurately measure a full range of contaminants within the facility. Table 12.2a lists the current ISO 8573-1:2010 compressed air specifications. The figures for particulates differ considerably from those given in the earlier 2001 version of the standard reproduced in Table 12.2b. This highlights the need to specify which version is being referred to.

There are no legal definitions as to what constitutes a minimum level of cleanliness for air that is used in the manufacture of food (Fish and Froehlich 2012). In the USA, 3A 604-05 Accepted Practice (3-A 2004) provides guidance to the American dairy industry. A food-industry standard that is widely employed in many countries is set out in Section 6 of the British Compressed Air Society (BCAS)—British Retail Consortium (BRC) Code of Practice (BCAS/BRC 2006). The Code

Table 12.2 ISO 8573-1 compressed air purity classes

	Particulates				Water		Oil
	Maximum[b] number of particles per m^3			Mass concentration, mg/m^3	Pressure dew point, °C	Liquid, g/m^3	Total[b] oil (liquid and vapor), mg/m^3
Class[a]	0.1–0.5 µm	0.5–1 µm	1–5 µm				
(A) ISO 8573-1:2010							
0	More stringent than class 1 (specified by equipment user or supplier)						
1	≤20,000	≤400	≤10	–	≤−70	–	0.01
2	≤400,000	≤6,000	≤100	–	≤−40	–	0.1
3	–	≤90,000	≤1,000	–	≤−20	–	1
4	–	–	≤10,000	–	≤+3	–	5
5	–	–	≤100,000	–	≤+7	–	–
6	–	–	–	≤5	≤+10	–	–
7	–	–	–	5–10	–	<0.5	–
8	–	–	–	–	–	0.5–5	–
9	–	–	–	–	–	5–10	–
(B) ISO 8573-1:2001							
0	More stringent than class 1 (specified by equipment user or supplier)						
1	100	1	0	–	≤−70	–	0.01
2	100,000	1,000	10	–	≤−40	–	0.1
3	–	10,000	500	–	≤−20	–	1
4	–	–	1,000	–	≤+3	–	5
5	–	–	20,000	–	≤+7	–	–
6	–	–	–	–	≤+10	–	–
7	–	–	–	–	–	<0.5	–
8	–	–	–	–	–	0.5–5	–
9	–	–	–	–	–	5–10	–

[a] The purity of compressed air is specified by referencing the standard (ISO 8573-1:2010 or ISO 8573-1:2001) followed by the purity class for each contaminant (particulate matter, water, and total oil). A different purity class for each contaminant may be selected, if appropriate

[b] The reference conditions for the measurement of particulates and oil are 20 °C, 1 bar, and zero relative humidity

Table 12.3 Maximum contaminant levels recommended in BCAS/BRC (2006)

	Particulates[a] (maximum number per m^3)			Water (at air line pressure)	Oil[a]
Compressed air designation	0.1–0.5 µm	0.5–1 µm	1–5 µm	Pressure dew point, °C	Total oil (liquid and vapor), mg/m^3
Contact	100,000	1,000	10	≤−40	<0.01
Non-contact	100,000	1,000	10	≤+3	<0.01
Non-contact, where HACCP shows a high-risk area	100,000	1,000	10	≤−40	<0.01

[a] The reference conditions for the measurement of particulates and oil are 20 °C, 1 bar, and zero relative humidity

distinguishes between air that comes into direct contact with the food (contact) and air that could come into contact with the food (non-contact). It recommends the maximum contamination levels given in Table 12.3. These figures correspond to ISO 8573-1:2010 Classes 1.2.1 and 1.4.1 for contact and non-contact air, respectively. The Code also stipulates that the level of microbiological contaminants in the compressed air should not be detectable using the test method described in ISO 8573-7 (ISO 2003).

In order to meet the requirements of the Code of Practice, the compressed air must be treated before use to reduce the levels of contaminants to acceptable levels. In order to meet the requirement of a −40 °C dew point for air that comes into contact with food, an adsorption dryer is required to treat the air after it has cooled following compression. This should be located close to the compressor. In the case of non-contact air with the less stringent dew point requirement of +3 °C, a refrigeration dryer will suffice. In order to achieve the Class 1 rating for particulates and oil, two-stage (at least) filtration is required; this should be located as close as possible to the point of use. Fish and Froehlich (2012) recommend a high-efficiency coalescing filter with a rating of at least 99.99 % at 0.01 μm as the first stage, followed by a sterile air filter with an efficiency of at least 99.9999 % at 0.01 μm. Such a system will ensure that the food product is properly protected from contamination by the air.

12.7 Services

The services within a factory provide the required utilities to the equipment or their point of use. If any services fail or are difficult to upgrade or modify, this will cause major issues and could result in significant additional costs. Therefore, a good design of the services is vital. One has to bear in mind the following:

- Legal and safety requirements
- Possible future expansion
- Maintenance aspects—accessibility
- Cleaning and hygiene

The services will have to be run to most items of equipment and are therefore a major part of the factory infrastructure. They therefore contribute significantly to the capital cost and, over the life of the factory, are a large component of the operating cost. There is no one ideal design for the services but there are some guidelines which can help. In the fundamental design there are a number of main options, which are:

- Use a roof void or mezzanine level to run the services.
- Design the services as an integral part of the building structure.
- Use a false floor.
- Lay main cable trays and pipe routes.
- Employ a distributed approach to some services to reduce paperwork and cable lengths.
- Use telemetry for control, particularly on large sites.

The services will need to be accessible, as changes and future additions will undoubtedly occur.

12.7.1 Pipework

Pipes are required in the factory to allow services such as water, steam, gases, and refrigerant to be supplied to equipment in an efficient and low-cost manner. Running headers (main supply lines) for steam, water, etc., can be effective as long as they are sized for the possible future expansion of the factory. Although a higher initial capital cost is required, they do allow for a neater factory and a quick and low-cost means of supplying new equipment. However, if a capacity limit is met, this will require the complete system to be increased in size. Therefore, adequate initial sizing is critical.

It is a good practice to color-code the pipework to identify what it is carrying. If the pipework is located in the factory processing area, thought should also be given as to how it will be cleaned. A little planning beforehand can often save considerable time and expense later.

12.7.2 Lagging and Cladding

Pipework used to convey hot or cold fluids is normally lagged for several reasons. The lagging will reduce heat loss or gain and prevent condensation and freezing up of pipes. Also, from a safety angle, it will stop people burning themselves on hot or very cold pipes. When deciding on pipe runs, it is essential to allow for the size of the pipework including lagging and cladding. Any lagging materials used must be appropriate and, in some countries, specifically approved for use in the food industry. It should be easily cleanable as this not only provides a good aesthetic finish but is also hygienic.

12.7.3 Brackets and Supports

Any pipework and cables will need to be supported. It is important to ensure that the supports are adequate to prevent bowing and possible collapse. Brackets and supports need to be of such a design that they are hygienic, cannot harbor pests, and can be readily cleaned.

12.7.4 Cables

Cables for power supply or control have to run around the factory. Often there is a central motor control center and control room. It is therefore necessary to use a lot of cable. This has to be supported by some means. It is normally laid on trays, baskets, or in ducting or conduits. There is then the question of where the cables should be run—in a roof void, at low level, or at high level. The best decision will depend on a variety of factors such as the building design and budget.

12.8 Environmental Considerations

With everyone becoming more environmentally conscious, it is now necessary to consider in the design of the factory the environmental impact it may have. It is usually a requirement by the authorities to carry out an environmental impact assessment. In Europe, responsibility under the Integrated Pollution Prevention Control (IPPC) legislation has now been passed to the enforcement agencies (DEFRA 2010). In the USA there are similar specific EPA regulations (EPA 1991). Legislation in most countries now calls for the use of BATNEC (Best Available Technology Not at Excessive Cost) for the control of waste and pollution. This means that a factory must consider its waste streams very carefully along with the implications of installing treatment or abatement systems.

12.8.1 Liquid Effluent

Liquid effluent from food production is usually a result of washing down and cleaning-in-place (CIP). The acid or caustic chemical-based cleaning fluids allow for more effective cleaning, but they do then create a problem when they are discharged. Water from cleaning will usually have a pH that is either acidic or alkaline and needs to be neutralized. The discharge of liquid effluents into the local waterways is controlled in almost all countries. It is a minimum requirement of most authorities to remove solids, fats, and oils from the water before it is discharged into the municipal sewer or into a waterway. The typical types of systems are:

- Fat trap, which is pumped out periodically
- A separation tank
- Solids filter/screen to remove solids automatically
- Flocculation tank with dissolved air flotation to remove fat and other solids
- An intercept tank where the pH can be monitored and regulated and effluent held if there has been an upset

Biological oxygen demand (BOD) and chemical oxygen demand (COD) levels are determined by the authorities, who specify allowable consent levels. These should be checked before constructing a food factory; otherwise, one may find the need to build an on-site treatment plant, which can add significantly to the capital cost.

12.8.2 Gaseous Emissions

The raw materials, process, and the specific processing equipment will all determine the amount and type of gaseous emissions. It is obviously advantageous to use a "clean" process rather than have to resort to the use of an abatement system. One should take into account that if the authorities do require an abatement system, it is likely to be expensive. It is therefore better to try and eliminate the problem at source.

Emissions fall into several categories; toxic ones are obviously the worst, followed by obnoxious or irritating but nontoxic odors. Consent limits for toxicity and acceptable levels of odor will partly depend on the location of the factory. Odorous emissions occur from most processes but more obnoxious odors are obviously more noticeable. Some basic considerations are:

- Local authority and legal requirements
- Prevailing wind direction
- Readiness to dilute
- Normal air velocity
- Height of the stack if one is required
- Choice of abatement system if one is required

If odorous emissions do cause a nuisance and need to be treated, there are a number of different technologies available such as biofilters, thermal oxidizers, chemical treatment methods, and the use of masking agents.

12.8.3 Solid Waste

Most food factories produce some solid waste, so it is essential that sufficient space be allocated on the site for waste treatment, storage, or handling facilities. Most of this waste is likely to be packaging material, which is created during the packaging process. Some processes may also generate significant quantities of waste product, which is rejected for whatever reason, and then needs to be disposed of.

For packaging waste it is usual to use a compactor to compress it and minimize its volume. This reduces subsequent transport, recycle, landfill, or incineration costs. It is important to think about the best location for the compactor. It should be easily accessible but hidden from sight. The area in which it is kept should be readily cleanable so as to provide a good environment. Invariably waste materials are kept at the back of a factory and create an eyesore and attract pests and vermin.

For waste product, it may be possible to recover food that is safe to use as an ingredient in an alternative lower cost product. Alternatively, another company may be willing to buy it for reprocessing or for animal feed. If the waste is to go to landfill, it is important that it is handled in an appropriate manner so as not to create other problems such as attracting pests. Many insects and rodents are attracted to waste food, particularly when it is left outside the factory building for an extended period of time. It is therefore essential to select a good location for waste-food containers or skips, which can be properly cleaned down. Any container should be designed to prevent the entry of vermin.

References

3-A (2004) “Supplying air under pressure in contact with milk, milk products, and product contact surfaces”, 3A 604-05 Accepted Practice, 3-A Sanitary Standards, Inc., McLean, VA, adopted 21 November.

American Federal Standard (1992) “Standard for airborne particulate cleanliness classes in clean rooms and clean zones”, FD209E, General Services Administration, Region 7, Ft Worth, Texas 76102, USA. Available online at www.set3.com/papers/209e.pdf.

BCAS/BRC (2006) “Food grade compressed air: A code of practice”, British Compressed Air Society and British Retail Consortium, London. Available online at http://www.airpower.co.uk/assets/docs/bcasfoodgradecode.pdf.

Bartholomew, A. (1987) (ed.) “Food factories (processes, equipment, costs)”, VCH, New York, ISBN 3 527 26490 6.

CCFRA (1993) “Guidelines for the design and construction of floors for food production areas”, TechnicalManual No. 40, Campden & Chorleywood Food Research Association (now Campden BRI), Chipping Campden, Gloucestershire GL55 6LD, England.

CCFRA (1996) “Guidelines for air quality standards for the food industry”, Technical Manual No.12, Campden & Chorleywood Food Research Association (now Campden BRI), Chipping Campden, Gloucestershire GL55 6LD, England.

DEFRA (2010) “Environmental permitting guidance. The IPPC Directive. Part (A1) Installations and Part (A1) Mobile Plant. For the Environmental Permitting (England and Wales) Regulations 2010”, Version 3.0, Department of the Environment, Food and the Regions, London, March. Available online at http://www.defra.gov.uk/publications/files/pb13634-ep2010ippc.pdf.

EPA (1991) Environmental Protection Act, Commencement 1, Order SI No 2226 (1991), ISBN 0110052269.

Fish, A. and Froehlich, P. (2012) “Compressed air contamination in the food industry”, FoodSafetyTech, 14 June, http://www.foodsafetytech.com/FoodQuality/News/Compressed-Air-An-Overlooked-Source-of-Contaminati629.aspx.

Haines, R.W. and Wilson, C.L. (2003) “HVAC systems design handbook”, 4th edit., McGraw Hill, New York, ISBN 0 07 1395865.

Holah, J. and Lelieveld, H.L.M. (2011) (eds) “Hygienic design of food factories”, Woodhead, Cambridge, ISBN 879-1-84569-564-4.

IFST (2007) “Food and drink—good manufacturing practice: A guide to its responsible management”, 5th edit., Institute of Food Science and Technology, London, ISBN 0 905367 20 0.

Imholte, T.J. (1984) “Engineering for food safety and sanitation”, Technical Institute of Food Safety, USA, ISBN 0-918351-00-6.

ISO (2003) “Compressed air—Part 7: Test methods for viable microbiological content”, ISO 8573–7:2003, International Organization for Standardization, Geneva.

ISO (2010) “Compressed air—Part 1: Contaminants and purity classes”, ISO 8573–1:2010, International Organization for Standardization, Geneva.

Jowitt, R. (1980) (ed.) “Hygienic design and operation of food plant”, Ellis Horwood Ltd, Chichester, England.

Lelieveld, H.L.M., Mostert, M.A., Holah, J. and Ehite, B. (2003) (eds) “Hygiene in food processing”, Woodhead, Cambridge, ISBN 978-1-85573-466-4.

Lelieveld, H.L.M., Mostert, M.A. and Holah, J. (2005) (eds) “Handbook of hygiene control in the food industry”, Woodhead, Cambridge, ISBN 978-1-85573-957-4.

Marriott, N. G. and Gravani, R.B. (2006) “Principles of food sanitation”, 5th edit., Springer, New York, ISBN 0-387-25025-5.

Mattingly, C.T., Elson C.R. and Whitman W.E (1980) “Food factory design”, BFMIRA (now Leatherhead Food Research), Leatherhead, England.

Mortimore S. and Wallace C. (2000) “HACCP- A practical Approach”, 2nd edit., Aspen, Gaithersburg, MA, ISBN 0-8342-8.

Peters, M.S., Timmerhaus, K.D. and West, R.E. (2003) “Plant design and economics for chemical engineers”, 5th edit., McGraw-Hill, New York, ISBN 0-07-239266-5.

Sprenger, R.A. (2009) “Hygiene for management”, 115th edit., Highfield Publications, London, ISBN 1 906404-71-0.

Stranks, J. (1995) “Occupational health and hygiene”, Pitman Publishing, London, ISBN 0 273 60908 4.

Wallin, P.J. (1997) “Food factory design and operation” Chapter 17 in “Food industries manual’, 24th edit., (eds) Ranken, M.D., Kill R.C. and Baker, C.G.J., Blackie Academic & Professional, London, ISBN 0-7514-0404-7.

Wallin, P.J. and Haycock, P. (1998) “Foreign body prevention, detection and control”, Blackie Academic & Professional, ISBN 0-7514-0416-0.

Chapter 13
Construction: Techniques and Finishes

K.P. Sutton

13.1 Construction Techniques

This chapter provides a comprehensive description of construction and finishing techniques employed in food factories. The first topic covered is the ground floor slab, which should be capable of withstanding all structural, thermal and mechanical stresses and loads that will be imposed on it during service. Superstructure designs are then considered. Most (but not all) food factories are accommodated in single-storey widespan buildings based on a steel framework fabricated in advance off-site and erected on prepared foundations. This and alternative techniques are described. Roofing requirements are then considered, followed by a description of the construction of external and internal walls and commonly applied finishes. The specifications for floors, ceilings and lighting are then addressed as are those for internal drainage systems. The chapter concludes with sections describing doors and windows, hand-wash facilities, and fire detection and protection.

The basic superstructure of the building will invariably be a steelwork frame, fabricated in advance off site, and erected on prepared foundations. Roofing and wall cladding systems are available, normally in the form of composite panels, which are manufactured under controlled factory conditions and assembled in large sections on site. This provides a rapidly formed weather-resistant envelope in which to start internal works.

Basic concrete technology has improved immensely over the last decade, allowing 24-h operations with laser-controlled accuracy. Fiber addition and other admixtures have reduced movement joint requirements to a minimum, allowing large bay construction in short timescales.

Most new factories now include the use of composite panels for internal walls and ceilings. These have removed the reliance on "wet" trades such as bricklaying and plastering, allowing fast and clean installation with minimal interactive programming.

Floor finishes are still reliant to a greater degree on the skill of the tradesman, but, even here, advances have improved efficiency markedly over recent years. Plain concrete is power-trowelled by rotating blades to a smooth dense finish. Resin applicators are generally providing a one-coat resin-rich system with "sledge" depositing on large areas and with fast curing times. Tiling has advanced with the use of "vibration" tiling to ensure complete bedding and fast tile laying with flowable resin jointing.

K.P. Sutton (✉)
Food Factory Design Ltd, 5 Bassetsbury Lane, High Wycombe, Buckinghamshire HP11 1QU, UK
e-mail: keithpatrick.sutton@btopenworld.com

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_13,

The combination of all these techniques with a simple yet detailed design brief will allow even the largest new food production facility to be built and commissioned within 12–15 months. Depending on the overall capital value and payback, it may be worth the client paying for 24-h construction (where possible) to reduce this to a minimum.

13.2 Ground Floor Slab

13.2.1 General Requirements

In both new and old structures, the substrate (floor slab) should be capable of withstanding all structural, thermal, and mechanical stresses and loads that will occur during service. It should remain stable while protected by the flooring and be provided with all necessary expansion, contraction, and crack inducement joints to enable it to do so. Failure of the slab to remain stable will invariably affect the stability of the flooring. In particular, movement in the slab, however caused, will often be reflected in the flooring.

Hydrostatic pressure and rising damp may, under certain circumstances, cause adhesion failure between the flooring and the substrate. Where this is likely to occur, such as in areas where the groundwater table is higher than the substrate and where external tanking has not been applied, pressure relief must be provided.

13.2.2 General Design

The floor slab should support an imposed loading in manufacturing areas of 10 kN/m^2 or any greater specific process plant loading where necessary. In plant rooms, 10 kN/m^2 should be used. Floor insulation may be required in small buildings.

The base normally consists of a flat concrete ground floor slab, reinforced with steel mesh or steel fibers, laid to a 150-mm minimum slab thickness or thicker. It should be designed by the structural engineer. Concrete should be a minimum of grade C30 (28-day strength 30 N/mm^2).

13.2.3 Membranes

In all cases, polyethylene sheeting (1,200 G) or similar water barrier material or damp-proof membrane should be used under concrete ground slabs, or such alternative as is demanded by site conditions to prevent rising damp.

13.2.4 Joints

Ground floor concrete slabs should be designed with expansion joints at a maximum of 30-m intervals and contraction or shrinkage joints at a maximum of 10-m intervals. Alternatively, a joint-free design philosophy may be engineered with the use of continuous reinforcement mesh or steel fibers to control the width of surface cracks.

13.2.5 Falls

Where wet manufacturing requires the finished flooring to fall to gullies or channels, then the slope will normally be within the range 1:40–1:80, with the objective of avoiding any surface pooling. Where resin flooring is to be used, the fall should be formed in the base concrete whenever possible. If this is not possible, a structural concrete screed bonded to the base should be provided.

Where other flooring types (mainly tiling) are to be used, the base concrete may be laid flat, and the falls formed either within the sand/cement bedding screed or by using a structural concrete screed of varying thickness prior to applying a bedding screed of constant thickness. Slopes should be kept as short as possible.

13.2.6 Suitability of an Existing Slab

Where a refurbished building is to be used, the first and, arguably, most important step in producing a lasting floor surface is the detailed survey of the existing slab. This should take the form of a detailed visual inspection to estimate the area involved and take note of any obvious floor problems and details required.

Answers to the following should be obtained:

(a) What is the design loading?
(b) Is the construction suitable for the proposed use?
(c) Is there an under-slab membrane?
(d) Does the membrane effectively lap with any wall damp-proof course?
(e) Is the proposed process use to be wet or dry?
(f) Are existing drainage channels suitable for the proposed use or are modifications required?
(g) If new drainage channels are required, can satisfactory joints be made with an existing membrane?
(h) Are the falls satisfactory?
(i) Are floor openings required? If so, will they affect the load capacity and can satisfactory joints be made with an existing membrane?
(j) Are there existing holding-down bolt holes? (If these have penetrated a membrane, can it be repaired?)
(k) What will the final floor level be in relation to surrounding areas?
(l) Will the floor be subject to vibration?
(m) Is the floor contaminated with fat, grease, paint, or old toppings?

Note: Some of the above information may be contained in company, architect, or local authority files.

The evaluation of three specific parameters using the measuring equipment discussed in this section is recommended. These parameters are slab strength, moisture content, and surface adhesion when resins are to be used:

1. *Slab strength*:
   For an overlay system to provide lasting performance, the basic concrete itself must be sound. The best technique for assessing this rapidly is the use of a portable "Schmidt hammer," which measures the compressive strength of the substrate (Wikipedia 2012). It is recommended that this be checked once every 10 m^2. The minimum acceptable compressive strength should be 25 N/mm^2.

2. *Slab moisture*:
   The moisture content of the substrate should be checked with a Vaisala at the rate of 2 tests per 100 m^2 (Vaisala 2012). This instrument measures the relative humidity of the air in a hole drilled into the slab. The maximum acceptable relative humidity for accepting a resin topping is 75 %. Once the topping is cured, the acceptable relative humidity may increase to 80 % for the vapor barrier class and 90 % for the breathable class.
3. *Surface adhesion*:
   All resin overlay systems rely on good adhesion to the prepared surface. This adhesion can be adversely affected by poor preparation, surface contamination, etc. The surface adhesion should be checked with a pull-off tester using the preparation/priming system most suitable for the floor prior to work commencing. This is particularly relevant where complex preparation is required, for instance, in an oil-contaminated area. A minimum surface adhesive strength of 0.75 N/mm^2 should be achieved.

13.2.7 Surface Preparation of an Existing Floor

The correct preparation of the substrate is a vital step in achieving a satisfactory bond between it and the floor topping. The following preparation techniques are recommended:

1. *Captive blasting or blastracking*:
   Using this technique, the substrate is shot blasted, and the resulting shot and debris removed by vacuum in one operation. This technique is fast and clean and ideally suited to preparing large areas of concrete. It may not be effective in removing some types of previous toppings (particularly "soft" systems such as chlorinated rubber paints) and in coping with deep-seated oil contamination.
2. *Mechanical scarification*:
   Using this technique, the substrate is treated with rotating tungsten-tipped blades, which pluck away the upper surface. This technique is slower than captive blasting and is usually dustier. It is, however, effective against virtually all previous coatings.
3. *Thermal preparation*:
   This technique, in which the concrete surface is heated by a high-temperature air blast, drives volatiles (moisture, solvents, or oils) from the upper concrete surface. When followed by immediate priming with a fast-curing, solvent-free priming system, volatile contaminants are sealed into the concrete and away from the all important bond line. This technique is recommended in conjunction with mechanical techniques on all floors known to be contaminated by oil or prone to rising damp. It is recommended that specialized contractors be consulted on the choice of technique at an early stage in the selection of a flooring system.
4. *Acid etching*:
   This should be avoided because of the risk of contamination.

13.3 Superstructure

13.3.1 General

The design of the superstructure will involve satisfying the conflicting demands of the principal design criteria, i.e., economics, program schedule, internal processes, future expansion, internal flexibility, adaptability, statutory regulations, and internal finishes.

13.3.2 Widespan Buildings

In general, food-processing facilities are required to be single-story, widespan buildings. Exceptions to this are flour mills, which require vertical processing, and high-bay warehousing.

The viable alternatives to a widespan production building are considered to be either:

- Portal frame or a steel-trussed beam. A portal frame is hygienically superior because it has significantly less exposed areas for dirt to collect. It also is more efficient and adaptable for the location of plant and services in the ceiling void.

  or

- Precast and prestressed concrete frame with “saddleback” roof beams.

To ensure the most appropriate choice, detailed discussions with the architect, structural engineer, and possibly a design consultant will be necessary. The beam strength/span ratio for steel is far superior to that of concrete. Typically, concrete beam depth/span ratios are 1:10, limiting spans to around 10 m. Economic steel roofs may span up to 40 m, depending upon the loading.

The related beam structure should satisfy the following:

- Flush internal services. To achieve this on external walls, all columns should preferably be placed outside the line of the inner wall.
- A column-free production area, if possible. If this is not practical, columns should be clad with the appropriate room finish. It is preferable to totally encase columns, usually with concrete, to prevent voids.

In all new building work, a suspended walk-on ceiling is hygienically preferable. In refurbishments this may not be possible due to lack of headroom. Under-purlin sheeting is then the next best solution.

Where a suspended walk-on ceiling has been designed, it must accommodate a roof void adequate to house all main service pipe work and ducts, ventilation ducts and plant, and also specified process equipment. There must be adequate height for maintenance access and safety. A height of 2.5 m is suggested between the ceiling and the lowest part of the structure.

The superstructure should support any equipment dead loads and also certain high-point loadings and all services live loads. These are in addition to snow, wind, and other basic design loads. Consideration should also be given to future adaptations.

13.3.3 Fire Protection

The superstructure must provide for full fire resistance, as required by statutory regulations and any additional local requirements. Where structural steelwork requires fire protection, intumescent paints are preferable to sprayed-on fibrous materials. The latter are prone to significant damage by the installation of services, creating debris, and long-term maintenance. Other types of fire protection such as plasterboard, supalux, or vermiculux boards may be suitable on a superstructure with little or no service installations.

13.3.4 Structural Steelwork

Structural steel should be fabricated and erected in accordance with current Standards, together with relevant statutory and other Codes of Practice. In Europe, the relevant Standard is EN 1993: "Design of Steel Structures"; this consists of 20 parts dealing with the different aspects of steel structure design (Eurocodes 2005–2007) and should be used in conjunction with EN 1990, EN 1991, and other relevant Standards listed in this reference. In the USA, ANSI/AISC 360–10 (AISC 2010) applies.

Steel that is to receive site painting as the finish should be shot blasted and primed with one coat of zinc-rich primer before delivery to site. Steel to be encased in concrete should be untreated after fabrication. Steel to receive spray-applied fire protection should be shot blasted.

13.3.5 Concrete Frames and Slabs

All concrete frames should conform to EN 1992 "Design of Concrete Structures" (or equivalent Standard). EN 1992 (Eurocodes 2004–2006) consists of four parts and should be used in conjunction with EN 1990, EN 1991, and other relevant Standards listed in Eurocodes (2004–2006).

In situ concrete suspended slabs should be a minimum of 150 mm thick to provide sufficient stiffness. The use of permanent metal decking systems is recommended for speed of construction and for ease of fixing under-slab services. These should only be used together with a suspended ceiling below. If slab soffits are to be exposed to the process below, then a fair-faced flat concrete finish is essential. Precast concrete slabs are not recommended for suspended manufacturing areas because of durability concerns.

All concrete columns and beams should have 50-mm chamfers to all corners.

13.3.6 Membrane

In suspended wet manufacturing floors, a damp-proof membrane is essential to prevent water penetration of the structure and lower floors. This may be waterproof-grade mastic asphalt, bitumen/rubber latex emulsion, or reinforced bituminous sheet membrane. If there is an existing membrane, it must:

- Still be intact
- Run up to the wall joint and be effectively sealed into the skirting

13.4 Roof

13.4.1 General Requirements

Roof pitch should range from a minimum of 4° to prevent ponding to a maximum of 12°. Where regular access is required, the roof pitch should be a maximum of 7.5°. Where membranes are proposed for a "flat" roof, a minimum fall of 1:40 should be used. The roof needs to be rain-, weather-, and pest-proof.

For economic reasons, the outer roof lining should normally be constructed from profiled plastic-coated long rib steel decking. However, planning restrictions may require a roof covering to blend in with surrounding buildings.

The following types of coverings are recommended for "flat"-roof applications:

- Single-ply membranes, constructed from rubber or PVC. Specialized contractors are required.
- Multilayer, high-performance roofing. This is polymer-modified bitumen and is supplied by most major manufacturers.

All hangers, bolts, etc., should be galvanized.

13.4.2 Ventilation

External ventilators should be of the low-silhouette variety and sited to meet ventilation requirements. They should be fitted with bird and insect guards.

Any roof voids should be fully ventilated, but pest-proof.

13.4.3 Roof Drainage

Gutters should be a minimum 150-mm box section galvanized steel. All outlets should be filled with balloon-type guards to reduce blockages.

Downpipes can be of UPVC, but lower sections in vulnerable areas should either be of steel construction or provided with adequate protection against collision damage.

Where valley gutters occur within the building, it is essential that they be insulated to avoid condensation on the underside.

13.4.4 Design Loading

The roof should be designed for the following superimposed loads:

- Access and snow 1.5 kN/m^2
- Services 0.5 kN/m^2
- Any specific major plant items

13.5 Walls

13.5.1 External Walls: General

There are many types of external wall available; the main types are listed below:

1. Profiled metal sheeting:
   Cladding should be profiled plastic-coated steel, long rib type, or similar. Cladding should not be taken down to ground level because of the risks of physical damage and infestation.

2. Brick and block:
   When used in conjunction with profiled metal cladding, traditional brick and block cavity walls should extend to standard door and lintel level above the ground.
3. Composite panel:
   Panels should be of sufficient thickness to ensure structural stability and adequate insulation. Large panels subject to high wind pressures will require a thicker section. If sheeting rails are to be avoided on internal surfaces, thicker sections will be required to span the room height.
4. Concrete:
   Concrete walls must have a smooth surface and be a minimum of 200 mm thick where traffic impact is possible. For aesthetic reasons, a patterned finish may be desirable on the outside.

All rainwater drainpipes, services pipes and cables, etc., must be sited unobtrusively, but preferably external to the process areas. Rodding access must be provided. They should be protected from traffic impact where necessary.

Window sills and frames, flashings, gutters, downpipes, fillers, and soffit boards should be constructed from maintenance-free material, such as aluminum, powder-coated steel, or PVC, and suitably colored to match the cladding.

Brick wall cavities should be securely closed off at their top. Use cavity ventilators to prevent rodent infestation.

13.5.2 Internal Walls: General

The finish applied to internal walls will vary between extremes due to its intended use. For warehousing of fully boxed goods, close-texture fair-faced blockwork will suffice, whereas high-care areas will require a virtually seamless paneling or resin system.

Listed below are the various types of internal wall finish:

A. Fair-faced brickwork
B. Fair-faced brickwork and paint
C. Fair-faced blockwork and paint
D. Blockwork with sand/cement render, set, and emulsion paint
E. Blockwork with sand/cement render, set, and gloss paint
F. Blockwork with sand/cement render, set, and epoxy or special paint
G. Blockwork and cladding sheet, e.g., Glasbord FRP sheets
H. Blockwork and cladding panel, e.g., composite or laminated panel
I. Blockwork and stainless steel sheet
J. Blockwork and tiles set on render
K. Composite panels

In order to simplify construction, or for speed of erection, it is often found to be more economic to construct all production areas with the same type of finish. This invariably ends up as composite paneling.

Table 13.1 should be used as a guide to minimum standards for room finishes.

Table 13.1 Minimum standards of wall finishes

	Type of wall finish	
Area	Solid wall	Cladding
Plant rooms	A, C, or D	
Water storage	A or C	
Electrical switchrooms	A, C, or D	
Engineers workshop	B, C, or D	
Boiler house	A or C	
Materials store (wrapped goods)	B or C	
Materials store (open goods)	D or E	
Debox areas	D or E	
Fruit washing	E or F	G or H
Vegetable preparation	E or F	H or K
Meat preparation	E or F	H or K
Dispense area	E	G
Mixing areas dry	E	G
Mixing areas wet	F	I
Dry production (open goods)	D or E	G
Wet production (open goods)	E or F	G
Production (goods enclosed)	C or D	G
Packaging	D or E	G
Dispatch	C or D	
Cold stores, freezers	H	K
Washing (box, tray, utensil)	F	I or K
High care		
Egg stores, meat stores	H	K
Fresh cream, fondant	H	K
Packing and topping areas (post oven)	H	K

13.5.3 Internal Walls: Finish Requirements

For production areas, an aesthetic, durable, hygienic, and easily sanitized finish is desirable. Ledges, gaps, sills, and all forms of cracks should be avoided. Careful attention should be given to internal finishings to allow for differential expansion between the structure and walls. The walls and finish should incorporate all necessary movement joints, suitably filled and sealed.

Vertical corners should be rounded, and external corners should have inset stainless steel or galvanized steel strips to protect against impact from internal transport and equipment.

Internal colors should provide complementary "harmonious" color schemes.

13.5.4 Wall Protection

Wall protection should be provided against the following traffic:

1. *Forklifts*	Guard rails made of 50-mm galvanized steel mounted into the floor, 200 mm off the wall or "Armco" crash barriers if necessary, or 300 mm × 300-mm-high arrised kerbing
2. *Trolleytraffic*	150-mm-wide × 150-mm-high arrised kerbing or wall or floor mounted guard rails
3. *Pedestrian*	100 × 100 arrised kerbing or 50-mm coving

13.5.5 Plaster

Plaster should be retarded semihydrate gypsum plaster conforming to class B as defined in BS 1191–1:1973 (BSI, 1973)—now superseded by BS EN 13279–1:2008 (BSI 2008a). The finishing coat should be neat plaster, and the undercoat should be sand and cement render.

On all double-door openings and external corners in production areas, the plaster arrises should be protected over their full height with 50 × 50 × 6-mm galvanized mild steel angles, with lugs welded on, and cut and pinned to the brickwork. Any other salient angles, including isolated columns, which are liable to damage from mobile racks, should be similarly protected with a proprietary-type column guard.

13.5.6 Blockwork

- Dense concrete blocks should conform to BS EN 771–3:2011 "Specification for masonry units. Aggregate concrete masonry units (dense and lightweight aggregate)" (BSI 2011), or equivalent Standard. The compressive strength should be as stated.

The surface should be free from voids for fair-faced work, and a sample block should be provided prior to commencement.

- Autoclaved concrete blocks with lightweight aggregate should also conform to BS EN 771–3:2011 (or equivalent Standard). The compressive strength should be not less than 7 N/mm^2.

The surface should be free from voids for fair-faced work, and a sample block should be provided prior to commencement.

13.5.7 Blockwork and Cladding Sheet

It is nearly always preferable to form the internal finish in solid construction, integral with the wall structure. Only when this is impossible should the use of cladding sheets be considered. Great attention to detail is required to prevent infestation and/or mold growth. FRP sheet, which has been widely used in the food industry, is recommended. It is available in long lengths or rolls, which reduces the number of horizontal joints.

If the cleaning procedure is just a wipe down, then a smooth panel is necessary. It is essential to have a reputable, experienced contractor fit cladding, as this will help to prevent problems with infestation.

Suitable methods of application are:

- Adhesive pad
- Thermoplastic drive rivets
- Profiled fixing and jointing sections

13.5.8 Tiles

Tiles used to be, perhaps, the most widely used form of hygienic wall covering, but their use now is not advised. The basic problem, even with the more durable tiles and with epoxy grout, is that they are susceptible to damage and that the multiple jointing, inevitably present, is always a potential source of trouble. Tiling relies heavily upon the skill of the installer in applying the tile and upon adhesion for each individual tile.

If tiling is to be used, the installation should be in accordance with BS 5385–1:2009 (BSI 2009a) and BS 5385–4:2009 (BSI 2009b). Part 1 is for normal conditions of use, and Part 4 is for specific conditions.

13.5.9 Polypropylene Panels

Polypropylene sheet is extruded by a number of British and continental companies. The material has a well-defined range of properties, and there are very few variations or derivations. It has superb impact strength, durability, and chemical resistance and is the least expensive of the standard cladding materials. However, it has two limitations: the rating for surface spread of flame is Class 4 (BSI 1997), and the coefficient of thermal expansion is high.

Polypropylene is normally used where Class 4 fire rating does not have any bearing—in abattoirs for instance. But it is important that the local Fire Officer and Environmental Health Officer (EHO) are contacted for clearance in each specific case where polypropylene is to be installed.

Thermal expansion is an inhibiting factor from the cosmetic and installation point of view. However, potential problems can be avoided by using the right cladding techniques.

13.5.10 PVC Sheet

Unlike polypropylene, several different types of PVC are available, each formulated or produced in a different way:

- *Pressed sheet* is normally used in a catering environment, where a wipe-down cleaning method is sufficient. If a pressure-wash system is to be used, then a tougher surface is required.
- *Expanded PVC*, such as Foamex, is very similar in its properties to the pressed sheet. The main difference is that air is injected during manufacture to reduce the weight of the panel. The fire rating is similar to that of pressed sheet, and the thermal conductivity is slightly better, but it has poorer impact and scuff resistance. Expanded PVC is normally used for ceilings rather than walls. Unlike many other expanded PVCs, Foamex has a closed-cell structure and therefore does not allow the ingress of moisture, as the open-cell types can.
- *Extruded PVCs* have similar properties to pressed sheet, except that the extrusion lines are usually visible and the surface quality is generally inferior to that of pressed sheet.

13.5.11 Linings and Sheets

These are a combination of resin with glass fiber, known as FRP or GRP. FRP products may be sprayed onto the wall or hand applied in alternative layers of resin and chopped strand matt glass fiber to form an in situ lining.

The suitability of applied FRP linings in a food production area must be questioned. The methods of application are sensitive to prevailing environmental conditions and heavily reliant on the skill of application, require a 3- or 4-day curing time during which the area has to be fully ventilated, and cause an unpleasant smell and mess. Therefore, they should not be considered for use in existing production units.

Instead, FRP sheet is a more preferable type of wall finish. It is a continuously cast product, available in longer lengths than most other claddings, hence reducing the number of horizontal joints. The method of application is similar to that for other claddings. Of all the cladding materials available, FRP sheet is probably the most durable.

The embossed surface of this material may present a cleaning problem, although the manufacturers claim that the surface is both smooth and readily cleanable. With the correct cleaning regime, FRP sheet has performed well in some UK food plants.

FRP does have a disadvantage in that, being a thermosetting material, as distinct from PVC and polypropylene, which are thermoplastics, it cannot be thermoformed. However, preformed internal and external sections, which match the surface finish of FRP sheet, are available.

The absence of thermoplasticity, however, makes the FRP material more suitable than polypropylene and PVC sheets for environments that experience wide fluctuations in the ambient temperature.

13.5.12 Cladding Criteria

No one material will necessarily give the complete answer in every environment. If a wipe-down cleaning procedure is to be used, then a smooth-textured panel is needed, and hence, the FRP sheet would not be suitable. However, if there is a risk of scuffing by trucks and trolleys, a smooth panel will easily get marked, whereas the embossed panel will not.

Infestation can occur behind some wall cladding systems, but this can be avoided by employing a reputable contractor, who will provide joints and seals that are impervious to all kinds of pests as well as moisture. Any failure in this respect will be due to faulty installation and not faulty materials. A cladding contractor with the right degree of expertise and technical knowledge should provide a completely impervious cladding system.

When specifying a cladding material, the following factors must be considered:

- What is the environment?
- Is impact resistance important?
- Are formed corners required?
- What is the cleaning procedure?
- How high is the cladding to go?
- Is color a consideration?

13.5.13 Cladding Installation

The nature of the substrate has a strong bearing on the choice of cladding, and hence, substrate preparation is a very important part of the installation of any wall covering. The experience and technical ability of the contractor are therefore vital.

It is essential to protect vulnerable areas, such as corners and edges. The coverings are for hygiene, not impact resistance, though some have greater impact strength than others.

Growth of mold and other infestations in the voids between the cladding and the substrate can be avoided by correct installation and sealing. Silicone mastics containing fungicide are available, but they must not be relied upon to prevent mold growth. The real answer is an effective cleaning and sterilization regime, which should be included in the specification.

13.5.14 Composite Panels

Composite or "sandwich" panels are being used increasingly for all types of food production units. They are available in a range of thicknesses and lengths up to 12 m to suit most applications. Their rigidity is dependent upon the type of facings, core material, and core thickness. They are not particularly resistant to impact, and hence, they are usually mounted on large concrete kerbs above the floor.

Over the last decade or so, many factory fires have resulted in total loss of the facility, and blame has been attributed to the prevailing use of expanded polystyrene cores in the composite panels. These cores have provided a huge "fire load," which, once alight, is almost impossible to extinguish without risk.

Cores are now available in polyurethane (PUR), phenolic foam, mineral wool, and most recently polyisocyanurate (PIR). Of these, the last two offer negligible fire risk, and manufacturers may provide fire test certification.

Several kinds of facing laminates are available, but not all are supplied by every manufacturer or with the required core material.

Stainless steel sheet should be used where the environment is particularly aggressive or where high temperatures and regular abrasion are expected, e.g., in wash areas and mixing areas and at oven ends. GRP and FRP sheet materials may be used in similar situations, but they will not provide the same durability as stainless steel.

For normal use, polyester-powder-coated steel sheet or "Foodsafe" laminate is sufficient to provide a hygienic, easily cleaned surface. Some paints are now available with a built-in biocide to counter spore development.

13.5.15 Floor/Wall Coving

Ideally, a plinth should form an integral part of the floor to act as a base for the divider walls. This, however, makes a semipermanent structure, which may not always be appropriate to the application. Therefore, many coves go straight onto the floor, giving rise to increased bacteriological hazards. If possible, the plinth method should be used as this minimizes the water permeating into the wall or cladding.

13.6 Floors

13.6.1 Introduction

The floor is arguably the most important feature of a food-processing facility. Regulations are very general, often open to interpretation, and do not provide practical advice on how to achieve the required standards.

Table 13.2 Guidance on the type of flooring suitable for different areas

Area	Flooring finish	Flooring type (refer to Sect. 13.6.6 for full description)
Warehousing, plant rooms, engineering workshop	Power floated concrete (with hardener)	A/B
	Granolithic	C
Dry production areas		
Pedestrian traffic only	2–4-mm self-leveling resin	E
	12-mm fully vitrified tiles (ceramic)	D
Trolley traffic or forklift traffic	18-mm vitrified tiles (ceramic)	D
	8–12-mm resin screed (heavy duty)	E
Wet production areas		
All traffic	18-mm fully vitrified ceramic tiles group A1 or B1 of BS 6431 grouted with epoxy resin	D
	8–12-mm resin screed with sealer coat (heavy duty)	E
"High-care" areas	8–12-mm resin screed with sealer coat (heavy duty)	E

Floor failures often result in lengthy disruptions of production and financial loss, while repairs are carried out. It is therefore essential not to reduce the flooring specification due to budgetary constraints but to provide a technically correct solution.

This section highlights and describes the main features of floors, which may need to be addressed during the course of a project. Table 13.2 gives guidance on the type of flooring suitable for different areas.

Vinyl sheet is not considered suitable for any permanent processing area and should only be used in amenities, offices, etc. Resin floors should be epoxy or polyurethane (for use in higher temperatures). See Sect. 13.6.6 "Type E" for full details of resin systems.

Steel floor tiles should be avoided due to their poor hygiene. Impact damage to floors should be avoided by removing steel wheels and steel legs on pallets, collettes, etc. If this cannot be done, then the steel floor tiles should be bedded and grouted in an epoxy mortar, not cement, to prevent the creation of numerous dirt traps.

13.6.2 User Requirements

Once the decision has been made that a new floor is required, it is most important that the end-user requirements are specified and fully understood by everyone involved in order to minimize the possibility of incorrect selection and early failure. These requirements are most likely to be met if a checklist in the form of a questionnaire is completed. An example of such a questionnaire is shown in Table 13.3.

With all the information available, the client should be able to discuss with specialized contractors the required flooring attributes. A trial area of the chosen system should then be laid to check slip resistance, cleanability, etc.

Table 13.3 Questionnaire to establish floor requirements

FLOOR REQUIREMENTS CHECKLIST		
1	Floor area	
2	Process to be carried out	
3	Trucking type(s)	
	• gross weight	
	• wheel type	
4	Impact loads from proposed operations	
5	Abrasion	
6	Equipment and machinery to be installed	
7	Any vibration anticipated	
8	Spillage–product	
	• quantity	
	• temperature	
	• thermal shock by large scale dumping	
9	What cleaning method is proposed?	
10	Cleaning chemicals which may contact the floor	
	• type	
	• concentration	
	• temperature	
11	What are existing falls?	
12	What falls are required?	
13	Will existing drains be adequate?	
14	Is an anti slip finish required?	
15	Existing floor	
	• ground or suspended	
	• construction	
	• topping	
16	Is any change in use anticipated?	
17	Any special conditions	

13.6.3 Movement Joints

Movement joints in floors are an essential requirement to prevent damage, not only as the result of temperature changes but also from many other factors such as changes in drying shrinkage, moisture absorption, deflection, and vibration. The stresses due to these causes may result in loss of adhesion of the flooring, cracking, or bulging.

Expansion or movement joints should be provided in the floor finishes at the following locations:

- Following all joints in the structural slab
- At maximum 10-m intervals in both directions (even for most resins)
- Around the perimeters of all rooms
- Around or adjacent to gullies and channels
- Around plinths and upstands

Joints should be arranged at the high points in the floor to minimize the contact time of liquids with the joint material.

Due to the fact that movement joints may be of considerable depth, a low-cost backup material, such as polystyrene, is used behind the more expensive sealant but must be compatible. It is pointed out in Section 2 of BS 5385–4:2009 that some sealants will support bacteria and mold growth and the Standard suggests suitable materials to be epoxide polysulfides, flexibilized epoxide, the harder two-part polysulfide sealants, and sealants containing fungicide silicone. For high-temperature service, the Standard states that polysulfide sealants and flexibilized epoxide sealants can withstand lengthy exposure up to 80 °C and short exposure up to 100 °C but that silicone sealants are satisfactory up to 200 °C. Wherever possible, movement joints in trucking routes should be avoided because the sealants have to be flexible and are not, therefore, capable of withstanding heavy loads.

Where unavoidable, the edges of the flooring should be reinforced. The Standard states that epoxide polysulfide and flexibilized epoxide sealants have the best resistance to impact but are suitable for small movements only. The harder polysulfide, silicone, and polyurethane sealants have a good degree of elasticity and tend to recover quickly after deformation.

In determining the width of an expansion joint, the coefficient of linear expansion, particularly of the flooring, is the most important consideration. Ceramic tiles obviously have the lowest value of any floor material, while epoxy resin the highest, some seven times greater.

13.6.4 Skirtings

The floor finish in all production areas should be of coved skirting, minimum radius of 50-mm or 150-mm minimum splayed (45°) skirting to all upstands, for wall protection and ease of cleaning.

13.6.5 Falls

In wet processing areas, the finished flooring should fall to gullies or channels. As indicated in Sect. 13.2.5, its slope will normally be within the range 1:40–1:80 to avoid any surface pooling. Where resin flooring is to be used, the falls should be formed in the base concrete whenever possible. If this is not possible, a structural concrete screed bonded to the base should be provided.

Where other types of flooring (mainly tiling) are to be used, the base concrete may be laid flat and falls formed either within the bedding screed or by using a structural concrete screed of varying thickness beneath a constant-thickness bedding screed.

13.6.6 Flooring Finishes

Selection of an appropriate floor finish involves the consideration of several equally important factors. These include hygiene, slip resistance, and durability. Hygienic floors should be impervious so as to prevent the absorption of moisture and bacterial and chemical contaminants. Thus, timber and porous concrete floors are not suitable and should not be used. The surface should also be capable of withstanding frequent and stringent cleaning. Slips and trips are one of the principal causes of accidents in food factories; see Chap. 7, Sect. 7.3.4. It is therefore a legal requirement that flooring with an appropriate slip resistance be selected. Several tests are available that may be used to assess slip resistance. Cook (2011) and HSE (2012) describe techniques for measuring the coefficient of friction and surface roughness of in situ floors using portable instruments and ramp tests on a sample of flooring to determine its slipperiness. Note that the slip resistance of a wet floor or one contaminated by, e.g., grease is much lower than that of a dry floor. Finally, the surface finish of the floor should be sufficiently durable to withstand the anticipated wear and tear to which it will be subjected.

The following flooring finishes are commonly employed in food factories:

1. *Type A—power-floated concrete*:
   A dense, very smooth surface is required which is visually flat and suited to the direct application of thin floor coverings. Any defect in the finished concrete, which shows through the floor finish, will not be accepted. Maximum permissible deviation from flat: 3 mm from a 3.00-m straight edge.
2. *Type B—power-floated concrete with surface hardener*:
   As above, but incorporating dry-shake metallic aggregate surface hardener, trowelled into the surface of the concrete in accordance with the manufacturer's recommendations. This provides a durable aesthetic finish.
3. *Type C—granolithic concrete*:

   (a) Monolithic:
   The mix contains 5–10-mm aggregate; proportions are 1:1:2 by weight. The 12–25-mm-thick monolithic topping should be laid within 3 h of the in situ concrete slab. The length and area of the bay should not exceed 4.0 m and 15 m^2, respectively. After compaction, the surface should be trowelled at least three times during next 6–10 h.

   (b) Topping:
   The mix has the same composition as that given in (a) above. However, a thicker screed will be required. The exact thickness will be designed to suit the actual requirements and laid as follows:

   - In one layer when the thickness is 40 mm or less.
   - In two layers when the thickness is over 40 mm. The lower layer should be thicker than the upper layer, and neither should be less than 20 mm. The upper layer should be laid as soon as the lower layer is fully compacted.

4. *Type D—ceramic tiles*:
   These should be fully vitrified (ceramic) tiles conforming to group A1 or B1 of BS EN 14411:2006 (BSI 2006), which are bedded and laid in strict accordance with the manufacturer's instructions by an approved specialist. The recommendations of BS 5385–4:2009 (BSI 2009b) "Wall and floor tiling. Design and installation of ceramic and mosaic tiling in special conditions" should be followed. In wet or severe conditions, pointing should be with a water-, acid-, and alkali-resistant epoxy jointing compound and laid on a sand and cement screed.

   In the last decade or so, the method of "vibration tiling" has been introduced with great effect in the UK. Fully vitrified 18-mm-thick tiles with 1-mm spacing lugs are used to provide aesthetically pleasing tile patterns. The tiles are vibrated by a roller platform into the prepared screed and slurry to ensure full bed adhesion. After setting, the 2-mm-wide joints are filled with low-viscosity resin, which completely seals the side faces of the tiles. This produces a completely impervious floor able to withstand severe impact and forklift abuse.

5. *Type E—resin-based seamless floors*:
   (a) For pedestrian traffic only (dry areas):
   A 2–4-mm-thick self-leveling resin is sufficient. Epoxy and polyurethane are recommended. Epoxy systems will deform above 60 °C. Polyurethane systems will deform above 110 °C.
   (b) For all processing areas:
   A resin-screed system (heavy duty) is required and should be a minimum of 8 mm thick. Below this thickness, the resin will not have the strength or durability necessary to withstand high-point loads, jet washing, etc. Temperature limitations are generally as above. Epoxies and polyurethanes are the recommended types. Polyesters can only be laid in small areas at a time due to high shrinkage. Methacrylates are not recommended due to their high odor during curing, but may be acceptable in new builds or where segregation from production is achievable.

A sealing coat is recommended in order to reduce permeability to a minimum. It is essential in wet areas and in high-risk areas. Some products do not require a sealing coat because they are “resin rich” and provide a complete seal as laid. As yet there are no universally accepted European Standards for resin flooring. However, BS 8204–6:2008 (BSI 2008b) provides a useful Code of Practice that defines eight classes of resin floors ranging from Class 1 (light duty) to Class 8 (very heavy duty). Details can be found at http://www.resinflooringsite.co.uk/Standards&Classifications.html.

It is essential to note that any free phenols will react with chlorine-based detergents to produce chlorinated phenol, which can be detected as low as parts per billion levels as a severe taint. The phenols may be present in the resin used to make it trowellable during placing. Ask all suppliers to provide proof of taint testing.

13.7 Ceilings

All new factories should aim to have suspended ceilings in processing areas in order to prevent contamination of exposed product from dust and services. This also applies to refurbishments on existing sites. Ideally this should be a walk-on composite panel ceiling.

Where there is insufficient height to incorporate a walk-on ceiling with adequate access, a lay-in tile system should be considered. These tiles should have a plastic-faced, smooth finish for hygiene reasons and should be clipped to prevent inadvertent lifting. Access requirements should be carefully considered where services run above the ceiling.

If neither form of suspended ceiling is appropriate, an under-purlin roof lining is necessary. Many proprietary types are available. This will leave only the main steelwork exposed, which should preferably be portal frame or similar to reduce ledges to a minimum.

In multistory buildings where concrete slabs are being used, their lower face may be designed as the ceiling, provided it is relatively flat (i.e., not formed with the use of permanent steel shuttering).

Fire compartments may be required above suspended ceilings, depending on their size. These may be formed with two layers of foil-faced Rockwool or similar stitched together to enclose fibers.

Before commencement of any work, the main roof must be inspected to verify that it is structurally sound and proofed against rodents, weather, and other causes of deterioration.

Walk-on ceilings should be designed to support a load of 0.25 kN/m^2.

The ceiling should be supported a minimum of 2 m below the lowest structural member in order to provide access to the services and roof. All services should be designed and routed above the ceiling and housed in the ceiling void area. Where a particular service is required (e.g., an electrical supply for an item of process equipment), the supply is run through the ceiling in a conduit to the point of application. It is important to seal any holes drilled using sealant.

Suspended ceilings are not to be used for the storage of process equipment. Only service and associated equipment should be housed above the ceiling. These should be mounted on their own support steelwork or suspended from the roof.

The ceiling should be sealed and should present a clean, flush, self-finished, and hygienic surface to the production area and should be suitable for periodic sanitation.

In order to prevent condensation, which may cause panel degradation, particular attention should be given to areas of high humidity and temperature. Ceiling suspension systems should be constructed from galvanized material. In the roof void, all steelwork should be assembled with locknuts where not welded.

Personnel access into the roof void should be provided at one end of the building, with an emergency escape ladder at the opposite end or as required by local Fire Regulations. Fire stopping may be required with fire doors between each section to permit access. A permit-to-enter system should be used in restricted areas.

Fixed lighting, emergency lighting, and fire detection should be installed in the roof space for maintenance and emergency purposes.

The roof/ceiling void must be included in a regular cleaning and maintenance program. It must be regularly checked for pests.

Further details of the design of ceilings in food factories have been given by Wessels (2011).

13.8 Lighting

13.8.1 General Lighting

Lighting must be sufficient for the processing area and show defects in process and hygiene. It should be provided in the most energy effective manner practicable.

Lighting must not alter colors in inspection areas and must avoid glare. All building entrances must be illuminated.

13.8.2 Luminaries (Light Fittings)

All light fittings should be fully sealed, and all glass protected with a polycarbonate diffuser or with a plastic sheath around the tube. They should be designed and fitted to minimize dust harborage. They must be easily cleaned and maintained.

Light fittings should be fluorescent, high-frequency, and krypton-filled tubes suspended beneath the ceiling or recessed in the ceiling with a flush diffuser. The light fittings must maintain a vapor seal between processing and production areas and the roof area above the suspended ceiling. Good-quality impermeable sealant should be used to fill all holes and crevices. Where appropriate, fittings should be specified to protect against the ingress of dust and vapor.

Emergency lights must be fitted to ensure safe access to all exits and to allow adequate illumination of key processes.

13.8.3 Lighting Levels

The recommended lux levels for production areas are shown in Table 13.4.

Table 13.4 Recommended lighting levels for production areas

Production area	Lux rating
Automated production area	400
Preparation area (where inspection or production is manual)	600
Floor process area (where inspection or production is manual)	600
Cold product stores	250
Mechanical plant rooms	250
Roof mezzanine (specific areas only)	200
Packaging automated	400
Packaging manual	600

13.9 Internal Drains

13.9.1 General

The purpose of the drainage system is to remove effluent from production and other areas without harming the product or causing a nuisance. Effluent from adjacent production areas should be segregated as specified by the plant layout and food regulations. The drainage system should also prevent water entering any chillers and freezers.

13.9.2 Layout

If possible, drains should not pass under major plant items. The ingress of rodents should be prevented by suitable traps. Provision should be made for drains to be easily cleaned and regularly inspected.

The internal drainage system within a production hall should be independent of those of other site buildings.

The use of clayware gullies and channels is not recommended, due to their poor hygiene and durability. Stainless steel is recommended. Some proprietary glass-reinforced concrete channels will withstand chemical aggression. Refer to manufacturers' literature. There must be a sufficient fall to prevent stagnant water and risk of backup from main drains.

13.9.3 Liquid Wastes

There is no automatic right to discharge trade effluent to any public sewer or watercourse. It can, with the written consent of the water company, be put straight into the local authority sewer. However, under the Public Health (Drainage of Trade Premises) Act 1937 (Regulations, 1937) and Public Health Act 1961 (Regulations, 1961), the authority may impose restrictions on the quantity, temperature, content, rate, and time of discharge of the effluent and at what point the connection to the sewer can be made. It is thus possible that wastewater will have to be pretreated in the works before discharge.

Up to a point, dilution of highly polluted water with cleaner effluents may be a cheap way of reducing the need for pretreatment. If, however, the authority specifies the total pollution load or limits the quantity of effluent discharged, this is not an answer. Generally, it is easier to pretreat a concentrated solution or suspension, so heavily contaminated water should be taken straight to the treatment plant. Any waste, which satisfies the local authority requirements, can be routed direct to the sewer. Balancing effluents that are highly variable in flow or composition can sometimes enable consent standards to be achieved.

Where more than one source of contamination exists, an expert evaluation of possible pretreatment strategies should be made. Generally, food wastes are treated biologically, but physical and chemical treatments may be more appropriate for some effluents, particularly those containing high levels of free or emulsified fats or suspended solids. Nearly all forms of treatment will produce a residual sludge, which must be disposed of in accordance with the Control of Pollution Act 1974 (Regulations, 1974) and the Environmental Protection Act 1990 (Regulations, 1990).

Certain wastes can attack materials from which drains are commonly constructed. Acids, even weak solutions, should not be brought into contact with cement mortar joints or concrete pipes and manholes. Sugars also attack cement. Organic solvents and hot wastes must not be sent down plastic drains. For these reasons, it is usually better to keep different effluents separate until after pretreatment, but each case must be judged on its own merits.

Four drainage systems should be provided: one for domestic foul sewage, one for surface water off roofs, one for surface water off roadways, and the main drainage system for handling normal trade waste. Trade effluent must only be combined with domestic waste or uncontaminated surface run off after the point at which the trade effluent is sampled and its volume measured, unless agreed otherwise in writing. Local taxes paid by the factory cover the reception and treatment of purely domestic sewage; provided this can enter the sewage system separately, there should be no further charge for such wastes.

Many food factory wastes will contain fats and edible oils, which should be removed in a proper trapping system. If this can be done without contamination, it may be possible to sell the materials separated for further processing. Most local authorities have very strict limits on the amount of fat or oil that is permitted to enter their sewers.

Volatile hydrocarbons and mineral oils must not be discharged to the drain. A proper interceptor may be required to remove accidental spillages and for road and parking areas.

Process plant design should allow for the vast majority of solid waste to be trapped before hitting the floor. Once on the floor, waste is generally washed away. Hence, if this can be kept to a minimum, effluent treatment costs will be reduced and there will be less system blockages.

13.9.4 Routing of Drains

It is essential to identify very wet areas, which can then be kerbed off or channel bunded.

The toilet drainage system must not run beneath the processing area, and, as this effluent can enter the public drains without further treatment, it should be kept in a separate system.

13.9.5 Floor Drainage

13.9.5.1 Falls

Satisfactory drainage can only be obtained by providing adequate falls to drainage points. Normally a fall of 1 in 60 is adequate and should be the aim, but for a tiled floor, which is only occasionally wet, a fall of 1 in 80 may be sufficient; for very wet conditions or if the surface is very rough, a fall of 1 in 40 may be required. Many factors have to be taken into account. Falls greater than 1 in 40 may result in safety hazards and cause problems for wheeled vehicles.

The slope of the floor should also be considered in light of its proposed finish. A self-leveling finish should not be laid on a steep fall, while trowelled resin finishes require greater falls than others because small depressions, resulting in pooling, are difficult to avoid. Hence, for resins, the surface regularity should be less than 3 mm in 3 m. Long fall lines should be avoided to ensure that discharges reach the drains as quickly as possible; in the case of suspended floors, long falls would require a thicker slab.

13.9.5.2 Layouts

There are several methods of obtaining falls to drainage points, which may be channels or preferably gullies. Outlets should preferably be of stainless steel for ease of cleaning:

1. *Transverse*:
   The floor slopes to a channel or channels running the length of the room, either at the perimeter or in the center. Provided that the distance is not too great, then a single perimeter channel may be used. However, if the area is too wide, then a perimeter channel on either side may be required.
2. *Saucer*:
   The floor is divided into regular-shaped rectangles, each one dished to a gully at its center.

13.9.5.3 Types of Channel

1. *Rectangular-section channel*:
   This type of channel is suitable for handling high volumes of liquids and solids, if present. It can be formed with ceramic tiles, but this may result in cleaning problems due to the square corners and would not be suitable for the passage of wheeled vehicles without reinforcement. Stainless steel is generally used, and the invert depth is usually less than for tile-formed channels. The channels should be designed to fall along their length to a gully outlet.
2. *Shallow channel*:
   This can be formed in a tiled or resin floor and can cope with medium volumes of liquid and solids, if present. It is often used at the perimeter and does not require a grating.
3. *Aperture channel*:
   Formed from stainless steel, this type does not require a grating due to its shape. It is suitable for handling medium volumes of liquids and some solids, if present. There may be some difficulty in cleaning this type, and it is not easy to check visually for cleanliness.

13.9.5.4 Gullies

Gullies have to be used in saucer floors. They should be made from stainless steel and incorporate a trap. Gullies must be correctly sized to cope with the flow and incorporate a basket to collect the solids if necessary. A minimum hopper of 250-mm square is recommended.

13.9.6 Underground Drainage

Drain runs should be in straight lines between manholes. Pipework less than 600 mm deep should be surrounded in concrete 100 mm thick with compressible boards at all joints. Drainage lines should be of vitreous clay flexibly jointed or PVC material, as appropriate.

Grease and fat interceptors should be provided for as required. Drains serving areas with a high quantity of solids in the effluent are to be 150-mm minimum.

Petrol/diesel interceptors should be provided for external areas, as required. Where these serve areas subject to rainfall, they may need to be of the bypass design. In the United Kingdom, the type of interceptor to be used should be agreed with the water supply company and/or the Environment Agency, as appropriate.

13.9.7 Upper Floor Drainage

Where foul drains from the upper floor penetrate through the ground-level processing area, stainless steel pipes should be used for hygiene and aesthetic reasons. In all other cases, PVC or cast iron drains running above ceiling level may be used. Fire stopping is required if these drains pass through a fire compartment.

All downpipes should be located adjacent to columns or within walls to protect them from physical damage. Rodding eyes should be provided.

13.9.8 Internal Manholes

Manholes should not be located under process plant, and, wherever possible, they should be sited outside the process area. The number of manholes should be kept to a minimum.

All internal manhole covers should be recessed and airtight, be fabricated from galvanized or stainless steel, have the same surface finish as the floor, and should be double sealed and screwed down. Pitch epoxy should be applied to the internal faces of the manhole to a minimum of 150 mm above benching to prevent rodent harborage. Manholes should be provided whenever a branch line cannot be rodded from its outlet position. Manholes should be of precast concrete or brick construction on concrete base slabs.

For further details on floor drains in food-processing areas, see Fairley (2011).

13.10 Doors

13.10.1 General Requirements

Access to processing areas from the outside should be via double doors and an air lock. An insect-trapping device should be installed in the lobby. Emergency exits should be made clearly visible. No glass should be used for emergency release bolts. Wooden doors and frames should not be permitted in production areas unless laminated by steel or plastic covering. Doors should be self-closing. Where necessary, the fire rating of doors must comply with the Fire Officer’s requirements.

13.10.2 External Doors

External doors to the production bays, packaging, and general stores should be power operated, of robust design, and of steel construction.

The installation must prohibit bird and rodent access between and underneath the doors when closed. Grids are required at all entrances where surface water may penetrate the production building. Main access doors should be sized to enable all major plant components to be moved into and out of the processing area.

All trucking doors/doorways should be protected by guard rails or posts. All unloading/loading entrances or docks should have canopies to protect goods during inclement weather.

All building doors should be capable of being securely locked or bolted. Consult with the Fire Officer to ensure an adequate means of egress.

13.10.3 Internal Doors

These may be:

- Horizontal sliding doors
- Flexible plastic or rubber overlap doors
- Roller doors
- Swing doors

They must not be faced with timber or glass. However, a polycarbonate vision panel is recommended for doors in corridors (see Sect. 13.11). Where horizontal sliding doors are used, channel floor tracks are to be avoided.

Doors needing protection from physical damage should be fitted with stainless steel or aluminum panels and edges. Frames will also need protection. Galvanized or stainless steel posts may also be used for protection.

13.10.4 Hatches

Hatches are to be designed to the same criteria as for doors.

13.11 Windows

13.11.1 General Requirements

Windows should be avoided in process areas. Where windows are used, no glass should be allowed. Windows in process areas should be unopenable to prevent entry to birds and insects. The ventilation system should be designed accordingly.

13.11.2 Materials of Construction

The frames should be of low maintenance material such as UPVC or aluminum. Joints between frames and walls should be sealed with a good-quality sealant such as a two-part polysulfide.

13.11.3 Glazing Materials

Polycarbonate, such as “Makrolon,” is the preferred glazing material. Consideration should be given to external windows being tinted for solar control.

13.11.4 Sills

Window sills should slope directly from the edge of the frame to avoid any horizontal surfaces. The angle should be 45° internally and 60° from the horizontal externally (to prevent perching by birds).

13.11.5 Insect Screens

Where openable windows are unavoidable, then insect screens should be installed to prevent entry by pests. The preferred type is a monofilament nylon 10 mesh fitted in a proprietary UPVC frame. These can be supplied by any of the leading pest-control companies. Screens should be removable for cleaning.

13.11.6 Vision Panels

Where these are required in doors or walls, they should be made of polycarbonate.

13.11.7 Fire Rating

If a fire rating is required, the use of special Georgian wired and laminated glass is recommended, or a “sandwich” of polycarbonate and Georgian wired glass.

13.12 Hand Wash Facilities

Hand wash facilities should be provided at all personnel entrances to production areas where foodstuffs are handled and should be knee, elbow, or electronically operated. They should have soap dispensers, paper towels with bins for disposing of them, and, where necessary, a hand sanitizer dispenser. Where an operation requires the use of a scrubbing brush to clean hands, a trough should be provided to store them in sanitizer solution.

Sinks should be constructed of stainless steel and free of any crevices or cracks, which might trap debris. A stainless steel splash-back plate should be mounted behind sinks to avoid splashing walls and permitting water to collect behind the sink. The sink drain should be connected via closed pipework to the drainage system to prevent any splashing from wastewater onto the floor.

Prominent notices must be displayed instructing all personnel to wash their hands after using the toilet and before entering any processing area.

13.13 Fire Detection and Protection

13.13.1 The Fire Authority

In the UK, the Fire Safety Order 2005 requires the ‘responsible person’, usually the owner, to carry out a fire risk assessment to take into account the safety of their employees and anyone else who may lawfully be on their premises.

The order lays out the matters to be covered and how they must be assessed, recorded, improved, instructed, maintained and trained (for employees).

The local Fire Authority have the legal duty to audit and enforce the Order by issuing ‘action plans’ or ‘notice of fire safety deficiencies’ followed by ‘Enforcement Notice’ or an ‘Improvement Notice’ and finally a ‘Prohibition Notice’.

Hence any new factory or an extension or internal alteration must have a Fire Risk Assessment carried out by a competent person. The introduction of more hazardous processes or storage are also key issues requiring an assessment.

13.13.2 Automatic Sprinkler Installations

Sprinkler systems are the most reliable general protection system available for buildings. An automatic sprinkler system should automatically detect fire, raise an alarm, and deliver water to the heart of the fire. They are particularly valuable for:

- Controlling fires occurring in the majority of hazardous processes
- Protecting raw material/product storage both in production areas and within dedicated warehouses
- Protecting buildings that require constant protection by reason of the values at risk or the vulnerability of the business to interruption by fire
- Protecting premises, which are not readily accessible by the public fire service
- Providing adequate fire protection in very large factories or warehouses where subdivision employing fire compartment walls is not possible

Sprinklers are heat-sensitive valves, which open at a set temperature, normally 68 °C, to produce a spray of water over a designated area or within storage racks. Normally, a proportion of the water is also directed towards the ceiling above the sprinkler head. These are spaced at set intervals to cover the whole of the area to be protected, but normally only those heads directly above a fire will operate.

Many fires are controlled by just two or three heads operating, and, for the majority of fires, a maximum of only 6–8 heads will come into action. The system should be installed throughout the building and in buildings communicating directly or indirectly with it.

Sprinkler systems should be designed, installed, and maintained by approved specialist firms. Adequate maintenance of installations is critically important.

Sprinkler systems are designed to protect:

- Specific levels of hazard presented by a trade or process
- Particular items of plant (with additional sprinkler heads placed strategically within or beneath the equipment)
- Specific storage methods or systems (including height of storage, types of goods, and packaging)
- A specific building layout including location of internal partitions and ceilings
- Either a heated or unheated building

13.13.3 Other Fixed Fire Protection

These include localized fixed gaseous, dry powder, or foam extinguishing systems to protect specific high hazard processes or computers vital to a business. They are also suitable for protecting concentrations of high-value electrical or electronic equipment, especially where its loss would seriously affect production, e.g., motor control rooms or centers.

13.13.4 Automatic Smoke or Heat Detection Systems and Manual Alarms

The most effective way of detecting a fire in its early stages is by the installation of an automatic detection system, which is in addition to the break glass point system required by law. However, the value of an automatic detection system is affected by the reliability of the signaling system or other arrangements to summon the public fire service and the speed with which effective firefighting can commence.

Detectors are normally designed to detect one characteristic of fire, usually smoke or heat. No one type of detector is the most suitable for all applications, and the final choice will depend upon the particular circumstances. Installations are designed for:

- A specific building layout, including the location of internal partitions and ceilings. This may also affect the positioning of break glass points.
- A specific occupancy. This can affect the type of detector used.

Automatic detection is particularly valuable in rooms or areas infrequently visited, e.g., switchrooms or roof voids, but ideally should be installed throughout premises. Installations should be analogue, fully addressable and installed by approved specialist firms. Signaling should be via an approved connection to an alarm center unless a site has a guaranteed 24-h manned security presence, having the responsibility for immediately calling the public fire service.

Special systems are available for the early detection of fires in computer rooms and in electrical and electronic controls such as those found in motor control rooms or centers. Adequate maintenance of such installations is important.

13.13.5 Hose Reels

Installations are designed for:

- A specific building layout including location of internal partitions
- A particular layout of production lines or storage aisles

Hose reels should only be used by specially trained members of fire teams.

13.13.6 Fire Hydrants

Fire hydrants are requested by the fire authorities or insurers resulting from a detailed site assessment. They should always be considered for large premises or those distant from public hydrants. Extensions to existing buildings, new buildings, or additional external storage areas will require the number and location of hydrants to be reviewed.

13.13.7 Fire Compartment Walls and Floors

These are used to separate:

- Particularly hazardous processes from other departments
- Production from storage areas
- Services from all other areas
- Offices from production and storage areas

Most importantly, they act as a means of spreading the risk, particularly in premises that are not equipped with a sprinkler system. In other words, they are used to separate equipment and stocks of very high value in processing or storage areas.

Many compartments, particularly in multistory buildings, are required by the Building Regulations. Fire resistance times ranging from 30 to 120 min may be specified. Therefore, it is important to maintain the integrity of:

- The walls, ceilings, or floors themselves
- Doors or shutters located within the walls
- Any cavity barriers under floors or within ceiling or roof spaces
- Any fire dampers installed in trunking penetrating compartment walls, floors, or ceilings
- Oil storage systems and fusible links

References

AISC (2010) “Specification for structural steel buildings”, AISI/AISC 360–10, American Institute of Steel Construction, Chicago, IL, 22 June 2010 (reprinted 2012), 610 pp. Available online at http://www.aisc.org/WorkArea/showcontent.aspx?id=26516.

BSI (1973) BS 1191–1:1973 “Specification for gypsum building plasters. Excluding premixed lightweight plasters”, British Standards Institute, London, 5 October, 1973.

BSI (1997) BS476-7:1997 “Fire tests on building materials and structures. Method of test to determine the classification of the surface spread of flame of products”, British Standards Institute, London, January, 1997.

BSI (2006) BS EN 14411:2006 “Ceramic tiles. Definitions, classification, characteristics and marking”, British Standards Institute, London, 30 March, 2007.

BSI (2008a) BS EN 13279–1:2008 “Gypsum binders and gypsum plasters. Definitions and requirements”, British Standards Institute, London, 30 June, 2009.

BSI (2008b) BS 8204–6:2008 “Screeds, bases and in situ floorings. Synthetic resin floorings. Code of practice”, British Standards Institute, London, 31 January, 2008.

BSI (2009a) BS 5385–1:2009 “Wall and floor tiling. Design and installation of ceramic, natural stone and mosaic wall tiling in normal internal conditions. Code of practice”, British Standards Institute, 31 July 2009.

BSI (2009b) BS 5385–4:2009 “Wall and floor tiling. Design and installation of ceramic and mosaic tiling in special conditions. Code of practice”, British Standards Institute, 1 January 2009.

BSI (2011) BS EN 771–3:2011 “Specification for masonry units. Aggregate concrete masonry units (dense and lightweight aggregate)”, British Standards Institute, London, 31 October, 2011.

Cook, K. (2011) “Hygienic floor finishes for food processing areas”, Chapter 17 in “Hygienic design of food factories”, (eds) Holah, J. and Lelieveld, H.L.M., Woodhead, Cambridge, 2011.

Eurocodes (2004–2006) “BS EN 1992:2004 Design of concrete structures”, Joint Research Centre, European Commission, http://eurocodes.jrc.ec.europa.eu/showpage.php?id=132. National Annexes describe particular requirements for EU countries in relation to the areas covered by Part 1 of the Standard.

Eurocodes (2005–2007) “EN 1993, Design of steel structures”, Joint Research Centre, European Commission, http://eurocodes.jrc.ec.europa.eu/showpage.php?id=133. National Annexes describe particular requirements for EU countries in relation to the areas covered by Part 1 of the Standard.

Fairley, M. (2011) “Hygienic design of floor drains in food processing areas”, Chapter 18 in “Hygienic design of food factories”, (eds) Holah, J. and Lelieveld, H.L.M., Woodhead, Cambridge, 2011.

HSE (2012) “Assessing the slip resistance of flooring”, Information Sheet GEIS2, Health and Safety Executive, May. Available online at http://www.hse.gov.uk/pubns/geis2.pdf.

Regulations (1937) “Public Health (Drainage of Trade Premises) Act 1937”. Available online at http://www.legislation.gov.uk/ukpga/Edw8and1Geo6/1/40/contents.

Regulations (1961) “Public Health Act 1961”. Available online at http://www.legislation.gov.uk/ukpga/Eliz2/9-10/64/contents.

Regulations (1971) “Fire Precautions Act 1971”. Available online at http://www.legislation.gov.uk/ukpga/1971/40/contents.

Regulations (1974) “Control of Pollution Act 1974”. Available online at http://www.legislation.gov.uk/ukpga/1974/40/contents. Amended by Control of Pollution (Amendment) Act 1989 (http://www.legislation.gov.uk/ukpga/1989/14/contents).

Regulations (1990) “Environmental Protection Act 1990”. Available online at http://www.legislation.gov.uk/ukpga/1990/43/contents.

Vaisala (2012) “Humidity instruments”, www.vaisala.com/en/products/humidity/Pages/default.aspx.

Wessels, F. “Hygienic design of ceilings for food factories”, Chapter 16 in “Hygienic design of food factories”, (eds) Holah, J. and Lelieveld, H.L.M., Woodhead, Cambridge, 2011.

Wikipedia (2012) “Schmidt Hammer”, http://en.wikipedia.org/wiki/Schmidt_hammer. Last updated 11 February 2012.

Part III
Utilities and Services

Chapter 14
Steam Systems

N. Riches

14.1 Introduction

The production of steam from a boiler is a very old and well-tried technology. Advances in this field tend to involve the development of existing plant, and it is primarily in the area of controls that recent significant improvements have been achieved. The boiler plant considered here comprises small and medium sized installations, fired by conventional fuels, with individual outputs of up to 20 MW. Boilers in this range represent more than 90 % of the total installed capacity.

Why choose steam? The simplest explanation is that steam is a convenient means of transporting heat from the fuel being burned in the boiler to the point in the process where it is required. The advantage of steam is that it not only contains the sensible heat that water will contain but also incorporates the latent heat required to evaporate the water. This latent heat content is much greater than the sensible heat content and is released at a constant temperature. The importance of the latter property should not be underestimated, as it is a basic requirement for most industrial processes.

14.2 Water

The large quantities of water consumed by industry and commerce are either supplied by the local water company through the mains water system or abstracted directly from rivers or boreholes. During the water cycle, water can become contaminated by gases from the atmosphere and by dissolved minerals from the ground.

N. Riches (✉)
Steam Systems, 40 Mount Road, Penn, Wolverhampton WV4 5SW, UK
e-mail: neil.riches@btinternet.com

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_14,

14.2.1 Impurities in Water

The following impurities are often found in water:

Dissolved inorganic salts	Calcium, magnesium, sodium, chloride, carbonate and bicarbonate compounds
Suspended inorganic materials	Clay, silt, sand
Dissolved organic compounds	Humic acids, plant and animal decay products
Suspended organic materials	Oils, organic detritus
Dissolved gases	Oxygen, carbon dioxide, industrial fumes
Microorganisms	Bacteria, algae, fungi

Appropriate boiler feedwater treatment is extremely important, as the consequences of failure through corrosion or fouling can be catastrophic. Good quality water can become contaminated during use and, when it is to be recycled, the effects of process leaks and corrosion should be evaluated. For example, condensate from the steam distribution systems is often used to supplement raw water make-up; care should be taken to ensure that it does not contain any corrosion products, process contamination or dissolved gases.

14.2.2 Analysis and Control Parameters

The following parameters are commonly measured and used to control the quality of the water entering the boiler:

Hardness	Total hardness is the combined concentration of dissolved calcium and magnesium salts. *Temporary hardness* is caused by bicarbonates, carbonates or hydroxides. *Permanent hardness* is caused mainly by chlorides, sulfates and nitrates. Hardness is the most common contributor to boiler scaling
pH	A measure of the acidity or alkalinity of water. On a scale from 0 to 14, pH values below seven indicate acidic conditions and those above seven indicate alkaline conditions. The neutral point is at pH 7. The more extreme the pH, the more likely corrosion problems are to occur
Alkalinity	The extent to which a solution is alkaline and a measure of its hydroxide (caustic), carbonate and bicarbonate content. High alkalinity promotes foaming in the boiler leading to steam contamination
Silica	Found as dissolved silicate and in a suspended complex form. Can combine with other compounds to give scales that are strongly insulating and difficult to remove
Suspended solids (SS)	A measure of the particulate matter present in water. May be removed by filtration
Total dissolved solids (TDS)	A measure of the total amount of solids in solution, it is usually expressed as parts per million, milligrams per liter or grams per cubic meter. It is generally estimated on site by measuring electrical conductivity If the design values for TDS are exceeded, carry over from the boiler will increase leading to a deterioration in steam quality
Dissolved gases	Oxygen and carbon dioxide are the most important. Dissolved oxygen is an important factor in determining the corrosiveness of water. Dissolved carbon dioxide forms carbonic acid. Even this weak acid can lower the pH to values where the water becomes corrosive

The type of boiler, pressure, and heat flux dictates the techniques that can be used to achieve the required steam purity and efficiency. As the operating pressure or heat flux increase, the feedwater quality and control requirements become more stringent. Reference should be made to the guidelines issued by the boiler manufacturer and the appropriate code of practice in order to establish the maximum TDS tolerated by different boiler types.

Some of the above parameters—mainly alkalinity, hardness, pH and TDS—are used as routine controls in the management of boiler systems. If there is a discrepancy between the values determined by on site testing and target values, then control should be regained by increasing or decreasing blowdown or adjusting the dosage of treatment chemicals.

14.2.3 Effects of Impurities in Water

The impurities present in natural water, if used directly, give rise to corrosion, deposition and steam contamination. Good water treatment practice is necessary to overcome these problems. Industrial water treatment is usually achieved by external pretreatment to remove or modify problem mineral salts or internal treatment by adding chemicals or additives directly to the boiler water to prevent scale formation and corrosion.

14.2.3.1 Corrosion

The reduction or elimination of corrosion is important in preventing the loss of water and heat via leaks and avoiding high maintenance costs. The relative rate of corrosion of steel varies with boiler water pH and the level of dissolved oxygen. Good water treatment aims to keep the pH within the safe range of pH 8.2–12.5, while the addition of oxygen scavengers prevents iron being oxidized to ferric oxide or rust.

14.2.3.2 Oxygen Pitting

Oxygen pitting is localized corrosion characterized by small pits or holes. It is mainly found in steel condensate systems, but hot water systems and idle steam boilers can also suffer such attacks.

14.2.3.3 Caustic Attack

If too much alkali is added or allowed to concentrate, it can cause corrosion of the boiler metal. The attack may involve local dissolution of the metal, usually on high heat transfer surfaces, which have become fouled, or cracking of the metal.

14.2.3.4 Carbonic Acid Corrosion

Carbonic acid corrosion causes general thinning of pipe walls. The corrosion product is soluble in the acidic water and is thus carried back to the feed tank with the condensate return. On entering the boiler, this contamination can cause fouling of the heat transfer surfaces and loss of fuel efficiency. Contaminated condensate must therefore be discarded, leading to the loss of its heat content (around 20 % of the original heat content put in by the fuel).

Inhibition of corrosion in condensate systems is an important part of good water treatment practice. Other parts of the boiler system, e.g., feed tank, feed lines, pumps and valves, are also susceptible to attack and measures to inhibit corrosion also should be taken in these areas.

14.2.3.5 Deposits

Deposits in boilers cause two major problems, i.e., fouling of heat transfer surfaces and restriction of water flow. Since scale layers act as insulators, their presence reduces boiler efficiency and wastes energy. Some scales are worse than others, but even thin layers can have a significant impact. Deposition fouling of feedwater lines can restrict water flow leading to dangerously low water levels. In extreme cases, deposits can ultimately lead to catastrophic failure.

Deposits consist of impurities, which enter the system with the feed water or corrosion products formed within the system. Contaminants such as iron oxide, magnesium phosphate, oils, and grease also act as binders within deposits, making them sticky and difficult to remove, and certain deposits such as silicate can cause metal temperatures to rise to dangerously high levels where metal distortion can occur.

14.2.3.6 Scaling

Scaling in the boiler occurs when the solubility of a compound is exceeded, through either chemical reaction or increased concentration or higher temperatures. For example, calcium and magnesium salts dissolved in the feedwater become less soluble as the feedwater is heated and eventually precipitate out.

Hardness contributes significantly to scaling, particularly when water is heated.

14.3 Boiler Feed Water Treatment

14.3.1 External Treatment

External treatment of the raw water before it enters the pre-boiler system usually involves complete or partial removal of one or more types of impurity.

14.3.1.1 Base Exchange Softening

Sodium ion exchange, or base exchange softening as it is often termed, is the simplest and cheapest ion exchange process used in water treatment. As hard water is passed through the resin bed, calcium and magnesium ions in the water exchange with sodium ions attached to the resin. The exhausted resin is regenerated with salt (sodium chloride). Boiler scaling is avoided, as the sodium salts are much more soluble than the corresponding calcium and magnesium compounds.

Base exchange softening is generally used to treat the feedwater for low and medium pressure steam boilers and water heaters. Whilst this method will almost eliminate the hardness, there is no reduction in alkalinity, sulfate, TDS, chloride, or silica.

14.3.1.2 Dealkalization

Dealkalization, which reduces TDS by removing alkaline salts, can be considered as an intermediate ion exchange process. Dealkalization is generally used to treat the feedwater for low and medium pressure boilers.

14.3.1.3 Weak Acid Cation Exchange

In a weak acid cation exchanger, the less strongly alkaline impurities—carbonate and bicarbonate ions—are replaced by positively charged hydrogen ions. The carbonic acid that is produced is subsequently degraded and removed in a degassing tower. Provided the pH is acceptable and hardness has been reduced sufficiently, the degassed water can be used directly. If not, pH adjustment and base exchange softening are necessary. The weak acid cation resin is regenerated using a mineral acid (i.e., hydrochloric, sulfuric, or nitric acid).

14.3.1.4 Split Stream Dealkalization

This arrangement allows both hardness and alkalinity to be removed. In a split stream dealkalization plant, one stream passes through a strong acid resin bed and the other through a normal base exchange softener. In the strong acid stream, all the cations are exchanged for hydrogen ions to give carbonic acid and mineral acids. When the streams combine again, these acids react with the alkalinity in the softened stream to produce more carbonic acid. The carbonic acid is then removed as carbon dioxide in a degassing tower and the pH of the treated water adjusted.

Whilst this method removes almost all of the hardness and alkalinity and reduces the TDS, it does not reduce the sulfite, chloride or silica. The relative capital cost may be 3–5 times that of a base exchange softener and the operating costs may be 20–25 % higher.

14.3.1.5 Demineralization

This process removes dissolved solids using a strong acid and a strong base ion exchange resin in series. Passage of the water through the cation exchanger produces a solution of dilute acids, which are exchanged by hydroxide in the anion exchanger to give water. If carbonates and bicarbonates are present in the water, removal of carbonic acid in an intermediate degassing tower will reduce the requirements for hydrochloric exchange in the anion bed. This produces savings in both the capacity and regeneration requirements of the anion exchanger. The cation and anion exchangers are regenerated with mineral acid and sodium hydroxide respectively.

Where very pure water is required, the treated water can be passed through a mixed bed demineralizer containing a mixture of cation and anion beads. Alternatively, an additional cation exchanger can be positioned after the two-stage process to mop up any residual sodium hydroxide.

Demineralization is generally used to treat the feedwater for high pressure, high heat flux, and once-through boilers. This method removes all the hardness, alkalinity, TDS, sulfate, chloride, and silica. The relative capital costs may be 6–8 times that of a base exchange softener and the operating costs some 200 % higher.

14.3.1.6 Reverse Osmosis

In reverse osmosis, the water is pumped through a semipermeable membrane, which retains dissolved solids and silicate. The purified water passes through the membrane as the permeate. This is often acidic and pH adjustment is required to protect downstream equipment from corrosion. Although the capital costs can be 12–16 times higher than those for ion exchange and operating costs 20 % higher, reverse osmosis produces very pure water. Impurity rejection rates as high as 99.5 % are possible.

14.3.1.7 Deaeration

Deaeration is used primarily to remove dissolved oxygen from feedwater, by either thermal or chemical or mechanical means. Lower oxygen levels in the feedwater reduce the subsequent amount of oxygen scavengers needed and thus reduce chemical costs. The most common system uses steam to heat the water; as the temperature increases, oxygen is driven off. Free carbon dioxide is also removed in the deaerator, thereby reducing carbonic acid levels. Deaerated water should be stored and transported in such a way as to avoid reoxygenation. In the absence of a deaerator, the contents of the feed tank can be heated to reduce the dissolved oxygen concentration substantially. Returned condensate often provides most of the heat required.

The reduction in feedwater oxygen content can result in savings of up to 75 % in the amount of oxygen scavengers required. In addition, the high temperature of the feed reduces thermal shock at the entry to the boiler and allows the boiler output to approach its rated value more closely.

14.3.1.8 Plant Selection

The selection of the type of external treatment plant depends on the balance of demand, existing facilities, and process economics. Plant sizing depends on the quantity and quality of the water to be treated. Before specifying a size, it is important to obtain accurate information about water quality and plant performance. This will ensure that the water produced is within specification. If the composition of the raw water varies widely or the plant overruns, there is a serious risk that high concentrations of impurities could enter the boiler system.

Water treatment plant suppliers provide standard plant in a wide range of capacities and treated water delivery capabilities. The factors affecting the choice of external treatment technology and plant include:

- Flow rates, available and required
- Water pressure
- Storage facilities
- Type of boiler plant
- Steam or hot water duty
- Industry sector

14.3.2 Internal Water Treatment

With external treatment, there is always a possibility that impurities may escape capture and enter the boiler system as slippage. Internal treatment or conditioning of the water provides protection both for this and the possibility of plant overrun or other failure.

Internal treatments involve the addition of chemicals to the feed water to:

- Prevent scale formation and/or oxygen corrosion.
- Protect the metal surfaces from acid or alkaline attack.
- Ensure that any salts that precipitate out do not adhere to the heat transfer surfaces.
- Ensure that precipitated salts can be easily removed by blowing down.

Internal treatment regimes can be complex and depend on:

- The type of boiler.
- The chemical composition of the raw water.
- Whether or not the steam will be in direct contact with the process.

The Appendix lists the principal boiler feed water additives that have been approved for use in the preparation of steam that will come into contact with food. *Never use more of these chemicals than is absolutely necessary*. Not only are the chemicals themselves expensive, but they also add to the TDS content of the boiler water.

The pressure or temperature of operation of the boiler affects the stability of chemicals and the solubility of impurities and additives. As the pressure increases, the choice of treatment chemicals and the concentration permitted therefore become more restricted. The concentrations of impurities or additives tolerated also decrease as the heat flux increases, even at lower temperatures.

14.3.3 Chemical Dosing

Chemicals are added to three areas of boiler plant—the pre-boiler or feed system, directly to the boiler and the steam system. The amount of chemicals added is proportional to the mass flow through the plant and the level of impurities. In most cases, the dose is based on the feedwater flow and the steam flow for boiler water and condensate treatment respectively.

14.3.3.1 Dosing Methods

Chemicals need to be applied and maintained at specific concentrations for their desired effects to be achieved. If the levels are too high, chemicals are wasted. There may also be an increase in blowdown requirements. Both increase costs. An excess of the chemicals may even be counterproductive, with increased corrosion, deposition and deterioration of steam purity. On the other hand, if the levels are less than the minimum specified, the system will not be fully protected.

14.3.3.2 Intermittent or Continuous Additions

Treatment additions can be carried out either intermittently or continuously. With intermittent treatment, the dose is added at intervals so as to keep the concentration within the set limits for the period between additions. With this method, the frequency of additions should be matched to the depletion rate. However, the actual addition rate is often only once per day or once per shift. This is poor practice and leads to periods of over-treatment and under-treatment, with loss of effective protection. Continuous addition is preferred because the concentration of the chemical is held accurately within the set limits at all times.

14.3.3.3 Dilution of Treatment

Some chemicals are mutually incompatible at the concentrations used for dosage. Advice on mixing products should always be sought from suppliers and followed closely. However, there are a number of general rules that should be followed:

- Use good quality water such as demineralized water or condensate for diluting chemicals. Although softened water may be acceptable, hard water should not be used as precipitates may form in feed equipment, leading to low treatment levels and subsequent boiler failure.
- Since some of the treatment chemicals deteriorate with time at normal temperature, the tank mix should be prepared regularly. This may need to be done daily.

- Use only gentle stirring or agitation to avoid unnecessary aeration of the mixture.
- Hold mixtures or diluted chemicals in dedicated dosing tanks, which are constructed with inert materials, have a lid, are vented, can be easily cleaned and protected from extremes of temperature.

When handling and mixing chemicals, some essential safety points should be observed:

- Do not mix chemicals unless working to a specific recipe and instruction.
- The heat evolved when acid is mixed with alkali may cause explosive boiling.
- Toxic gases are given off when nitrates and hypochlorites are mixed with acid.
- Ammonia is given off when alkali is added to ammonium compounds.
- Mixtures of oxidizing and reducing agents create a fire and explosion hazard.
- Always refer to relevant data sheets.
- Safety precautions and restrictions should also be observed when segregating chemicals in storage compounds.

14.3.3.4 Dosing Equipment

Although the use of manually activated dosing equipment is an improvement on complete manual dosing, the use of automatic continuous dosing is recommended for reasons of safety and plant protection. Pumps should be selected so that the average volume to be dosed is achieved at the mid range setting of the pump. Motor-driven pumps are better able to deliver at high pressure than magnetic impulse pumps. For the pump to operate efficiently its design delivery pressure should be able to overcome the total system back pressure by at least 1 bar (14.5 psig), otherwise, the delivery volume may fall by 10–20 % near the maximum working pressure.

14.3.3.5 Dosing Position

Oxygen scavengers should be dosed into the system as far from the boiler as possible to provide sufficient reaction time. Dosage into the storage section downstream from a deaerator is common. If there is no deaerator, dosage should be into the feed line, but as close to the feed tank as practicable. The addition should always be after the last air contact region. Chelants should be added to the feedwater line after the feed pump and oxygen scavenger dosing point. Stainless steel quill injection fittings should be used. Phosphates are normally fed directly into the boiler, but if polyphosphates are used, these may be injected into the feedwater line.

Other chemicals, neutralizing amines, anti-foams, alkali and conditioners may be dosed to the boiler, the feedwater line or the feedwater storage section. Although filming amines may be fed to the boiler, injection by quill into a steam header is preferred. Neutralizing amines may also be dosed directly into steam lines to provide neutralizing capacity in selected areas in complex and extended systems.

14.4 Boiler Types

If operated correctly, all types of modern boilers are more or less equally efficient at converting fuel into steam. Table 14.1 indicates the expected thermal efficiencies obtainable for different boiler types, based on the gross calorific value of the fuel.

Table 14.1 Thermal efficiencies of different types of boiler

Boiler type	Efficiency %
Shell boiler	76–80
Reverse flame	74–78
Steam generator	76–79
Water tube	78–82

Industrial boilers range widely in size and performance. They are often designed to burn more than one type of fuel (e.g., natural gas, with fuel oil as a standby) and operate at pressures up to about 125 bar (1,800 psia) and steaming rates up to 455,000 kg/h (1,000,000 lb/h). High-capacity package boilers typically generate from 4,545 kg/h (10,000 lb/h) to about 270,000 kg/h (600,000 lb/h) of steam. Such units are designed to operate at pressures up to about 115 bar (1,650 psia) and temperatures up to 510 °C (950 °F).

Although they may appear to vary considerably in their construction, all boilers consist basically of a furnace chamber in which heat is transferred directly from the flame by radiation and flue gas passages where the heat is primarily transferred by convection. Two-thirds of the heat transfer takes place in the furnace and the remaining third in the flue gas passages.

There are two fundamental types of boiler: the water tube, in which the water is contained in pipes and the hot combustion gases pass around them; and the shell or fire tube, where the opposite is true. All other boilers are derivatives of these two types and have been designed to meet either differing size or dimensional limitations, or differing operational requirements. For in depth descriptions of water tube and fire tube boilers, see, for example, Malek (2005) and Woodruff et al. (2005).

Water tube boilers tend to be considered only for large steam outputs, which often require superheated steam. They are rarely used for hot-water production. For most industrial and commercial applications, however, a multi-tubular shell boiler is more appropriate. Only if the requirement is for an individual output above 20 MW and/or at pressures above 25 bar (362.5 psig) or steam temperatures above 340 °C is it necessary to use a water tube boiler. The reason for this is that water tube boilers cost more to build for a given steam output than do multi-tubular shell boilers.

The shell boiler can be entirely factory fabricated, mounted on a skid with all its associated equipment such as feedwater pump, burner and control panel and then delivered to site. The output and pressure limits are, however, determined by the feasibility of transporting the completed unit from the factory to the site.

14.4.1 Water Tube Boilers

The output from water tube units starts at about 8 MW and rises to power-station-sized units rated at 2,000 MW and above. At the bottom of the range, units can be manufactured and delivered to the site in one piece. The larger units are manufactured in sections and delivered for site erection.

The traditional water tube boiler relies on water circulation occurring as a result of the thermal-siphon effect—the hot water in the boiler is lighter and rises, drawing in colder water at the bottom to replace it. A variation, which allows for a more compact design using smaller diameter tubes, is the forced circulation boiler, where the feedwater is pumped through the water tubes.

The major potential problem with this type of boiler occurs whenever a power failure stops the circulating pumps. Steam is generated within the tubes and this can lead to overheating of the metal, softening and subsequent tube failure unless the fire can be rapidly drawn and cooling air can be provided at the convective tube bank. This type of plant cannot therefore be used in a fully automated, unmanned boiler house.

One of the main advantages of the water tube boiler in the 10–20 MW range is its ability to react to rapidly changing loads. The water tube unit contains only a fraction of the water in a shell boiler so the thermal inertia of the system is much smaller.

14.4.2 Multi-tubular Shell Boilers

Shell boilers began life as very simple units when it was realized that, if the fire under a closed vessel was bricked round, greater heat transfer occurred. The next step was to put the fire into a combustion chamber inside the boiler, bringing the hot flue gases under and around the water tank. This is the basis of the "Cornish" and "Lancashire" boilers. To improve on this, the hot flue gases were then brought back through the boiler water in tubes known either as fire tubes or as smoke tubes.

As materials and manufacturing processes improved, thinner metal came to be used for the tubes allowing more tubes to be accommodated. At this stage in its development the basic boiler was rather long and thin and required a large boiler house area. By making the hot gases go backwards and forwards through a series of tubes, the boilers were designed to be shorter and fatter, and heat transfer rates were improved. The modern multi-tubular packaged boiler is the logical conclusion to this evolutionary process.

The packaged boiler is so called because it comes as a complete package. Once delivered to site it requires only the steam and water pipework, fuel supply and electrical connections to be made for it to become operational.

These boilers are classified by the number of passes—the number of times the hot combustion gases pass through the boiler. The combustion chamber is taken as the first pass after which there may be one, two or three sets of smoke tubes.

The most common type of boiler is a three-pass unit with two sets of smoke tubes and the exhaust gases exiting through the rear of the boiler. Older two-pass units transfer heat less efficiently, fewer smoke tubes giving a smaller heat transfer area and the flue gases still containing considerable heat when they leave the boiler. Many such units have had equipment fitted to recover some of this potentially lost heat into the boiler feedwater.

Four-pass units are potentially the most thermally efficient but fuel type and operating conditions may prevent their use. When this type of unit is fired with heavy fuel oil or coal at reduced output, the heat transfer can be too good. As a result, the exit flue gas temperature falls too low causing corrosion of the flues and chimney and possibly of the boiler itself. The four-pass boiler unit is also subject to high thermal stresses, especially if large load swings occur suddenly; these can lead to stress cracks or failures within the boiler structure.

Another classification is related to the chamber at the end of the combustion chamber before the hot gases enter the smoke tubes. If this chamber is entirely contained within the water shell it is classified as a "wet back" boiler; if the chamber is refractory mounted on the outer plating of the boiler, the boiler is classified as a "dry back" unit. The wet back configuration reduces the number of smoke tubes and hence, marginally, the boiler size by increasing the heat transfer area at the point where the flue gases are hottest. Multi-tubular shell boilers are available which will fire any of the conventional fuels or any form of industrial or commercial waste.

The original convention was to produce two types of shell boiler—one with a small combustion chamber and many smoke tubes for firing gaseous or liquid fuels; and one with a larger diameter combustion chamber and fewer smoke tubes for firing solid fuels. Older units were also separately designed for gas and oil firing, again because of the combustion characteristics of the two fuels. Many of the older oil-fired units had to be de-rated when converted to gas firing. Some modern units, however, are manufactured with an intermediate size of furnace tube and are capable of firing all three fuels.

Recent design trends have been towards incorporating many more smoke tubes of a smaller diameter in the boilers to make them more compact. However, one of the major advantages of the older types of shell boiler is their very large water content, which provides a large potential steam reservoir during periods of rapidly increasing load. The large water surface area also results in drier steam. Modern designs eliminate this advantage, making shell boilers behave more like water tube units, but at the same time the lower water content of the modern boilers means that they can generally be heated through and brought on-line more quickly.

Boilers rated up to 12 MW are usually supplied with a single burner or stoker and those between 12 and 20 MW with two burners or stokers, each in a separate furnace chamber. In some of these twin-furnace units, the flue gases from each chamber are kept separate until they meet at the boiler exit. The advantage of this is that it is possible to operate the plant with only one burner firing, giving a much lower minimum output from the boiler. If the flue gas passages are combined, single burner firing may result in the flue gas temperature falling too low, thereby causing corrosion.

Multi-tubular shell boilers dominate the market for outputs between 3 and 20 MW. Even below 3 MW, derivatives of this basic design predominate.

14.4.3 Reverse Flame Boilers

The major problem with multi-tubular shell boilers is thermal stress brought about by differential expansion. The expansion of the furnace tube is much higher than for the first pass of smoke tubes—and this, again, is higher than for the second pass. This puts stress on the tube plates supporting each end of the boiler. The reverse flame is an attempt to reduce the problem by using a “floating” combustion chamber. The combustion chamber is only attached to the front tube plate.

These boilers are still classified as three pass units but two passes occur within the combustion chamber as the flame reverses and only one pass involves convective smoke tubes. In practice the additional heat transfer from the second pass through the combustion chamber is relatively low making this design little better than a two pass conventional shell boiler.

The other main advantage of the reversing flame is that it reduces the length of combustion chamber required making the boiler more compact. Space is often a problem when hot water or steam boilers are installed within existing boiler houses or buildings, so the relatively small floor area required by a “thimble” boiler could be an advantage. As there are relatively few short smoke tubes in the final pass, heat transfer rates are low resulting in high flue gas exit temperatures. Heat transfer can be improved by increasing the turbulence within the flue gases, and many manufacturers fit metal spirals or turbulators within the tubes to improve efficiency.

Although units of this type are currently manufactured for both steam and hot water production and are available in the 150–3,500 kW range, they are used primarily for hot water rather than for steam. At the lower end of the range they are in direct competition with cast iron sectional boilers and at the upper end of the range they compete with conventional multi-tubular shell boilers. The flame shape requirement means that only fuel oil or gases can be used, and most boilers of this type operate most efficiently when fired on fuel oil.

14.4.4 Steam Generators

Steam generators are derived from the water tube type of boiler. In practice they are small forced-circulation water tube boilers. As manufactured they are very compact, lightweight and capable of producing steam very rapidly from a cold start-up. They therefore react very quickly to load fluctuations.

Unlike the conventional water tube boiler, there is no steam/water separation header drum. The water, as it is pumped through the combustion chamber, partially flashes into steam, and then passes through a steam separator so that dry process steam is available. The water from the separators is then returned to the feedwater for recirculation.

Heat transfer rates can be improved by reducing the stagnant layers of gases and water that adhere to both sides of a heat transfer surface: this can be achieved stirring or increasing the turbulence. Fundamental to the design of a steam generator is the maintenance of a high level of turbulence in both the water and flue gases: this ensures high heat release rates and good thermal efficiency. Its small physical size, lightweight construction and rapid steaming potential make this type of boiler especially suitable for decentralized steam distribution systems. It does, however, have two disadvantages: because of its very high evaporation rate good feedwater quality is essential, usually necessitating the use of demineralized water; secondly, the steam generator does not cope well with high impulse steam loads.

Where a high peak demand occurs for a relatively short period it is better practice to fit a smaller steam generator together with a steam accumulator which gives a reserve of steam similar to that provided by a conventional shell boiler. Steam generators are manufactured to provide outputs ranging from 75 to 5 MW. Their major advantage is that they occupy very little space, even when allowance is made for water treatment equipment. They can therefore be sited almost anywhere within a factory. This means that if new equipment is installed requiring steam at, say, 10 bar, and if the existing steam distribution system is at 7 bar, a single generator dedicated to that new equipment can readily be installed. The alternative is to increase the existing distribution pressure, which may not be possible from an engineering point of view: even if it is feasible, heat and leakage losses will significantly increase.

14.4.5 Boiler Selection

The first decision involves the selection of a steam system; the appropriate choice is usually very clear. The next step is to evaluate the overall size of the system and how the load is likely to fluctuate. A large steady load ideally requires large boilers, but a load that fluctuates on an hourly, a daily or a seasonal basis will be met more efficiently if several smaller boilers are installed. The third step is to identify the appropriate boilers for the job. Generally, for each output level several boiler choices are available (see Fig. 14.1).

In all cases, when the selection of new or replacement boiler plant is undertaken, consideration should be given to the installation of Combined Heat and Power (CHP) schemes. For further details, see Sect. 17.2.2 in Chap. 17.

14.5 Fuels

14.5.1 Natural Gas

Because natural gas mixes so readily with air and burns without producing smoke and soot, boiler maintenance costs are low. Natural gas burners tend to be simpler with fewer mechanical parts and are also therefore cheaper to maintain.

Natural gas would normally be the preferred fuel for burning in boiler plant if convenience alone is considered. It does not have to be stored; in common with all the gaseous hydrocarbons it mixes

Maximum Steam Output	**Type of Boiler**
A. Below 1 MW	Steam Generator
High load swings and peaks	Steam Generator with Accumulator or Reverse Flame Boiler or Shell Boiler
B. Below 4 MW	Reverse Flame Boiler or Shell Boiler
C. Below 20 MW	Shell Boiler
Above 25 bar	Water Tube Boiler
D. Above 20 MW	Multiple Shell Boiler
Above 25 bar	Water Tube Boilers

Fig. 14.1 Boiler selection

readily with combustion air to burn cleanly; and, ideally the products of combustion are just water and carbon dioxide. These basic arguments would seem to carry a great deal of weight because the majority of new boiler installations in recent years have been gas fired.

The availability of an adequate gas supply at individual sites needs to be checked in advance as local constraints in the distribution system can sometimes lead to delays in providing a connection. A second factor is safety. Complying with legislation regarding the supply and use of natural gas involves some specialized equipment that has to be maintained.

Burning gas does cause pollution. Whilst the pollutants do not include smoke or noxious substances, they do include gases which contribute to the so-called greenhouse effect. Natural gas, being composed predominately of methane, is in itself one such gas.

Carbon dioxide, which is produced by the combustion of all fuels, is another; its production is not only unavoidable but also desirable as its presence indicates complete combustion of the gas. However, natural gas also produces oxides of nitrogen (NOx). This is because it burns at high temperatures and this provides the additional energy necessary to make the oxygen and nitrogen in the air combine.

As regards the pricing of natural gas, the actual price that a customer will pay, as for any fuel, depends on the amount used and the type of supply, and can vary over a wide range. Prices are generally competitive with oil products, for example with gas oil for firm gas supplies and with heavy fuel oil for interruptible supplies. Continued plant operation during interruptions of an interruptible supply requires a boiler to be dual-fuel fired, usually with oil as an alternative. In firing these two fuels, the burner would normally be set to achieve the most effective results on gas, because gas is used for most of the year, with oil firing only on the few days of interruption sometimes experienced.

14.5.2 LPG

LPG is used to describe two fuels: propane and butane. In practice, the vast majority of installations use propane. All the general comments about natural gas apply equally to LPG.

One major difference between the two fuels is that LPG requires both storage facilities and the special precautions needed in relation to leakage. The first can be very significant in terms of both the capital cost of a project and its overall operational and maintenance costs. The storage tanks involved are pressure vessels and therefore subject to both annual and long-term inspection and testing. If a customer owns his own tanks he is responsible for carrying out all inspections and tests at his own expense. In practice, most customers lease or rent the tanks from the fuel suppliers, eliminating both this responsibility and also that of general maintenance.

The second major difference is that LPG is heavier than air. If natural gas, which is lighter than air, escapes, all sources of ignition should be removed and windows opened. It will then disperse naturally. LPG, on the other hand, may find its way down into pipe ducts, cable tunnels, drains, cellars, etc., and will not disperse unless forced to using a fan. This characteristic influences the siting of storage tanks in relation to buildings, hollows, drains, cellars, etc., and plant location may be affected.

Although butane is usually cheaper than propane it is used less frequently because, when its temperature falls to 0 °C, it condenses. It therefore needs to be evaporated before it can be used, using either propane or electricity. The cost of this extra energy must be taken into consideration. It should also be remembered that the cost differential between propane and butane at times disappears altogether.

14.5.3 Fuel Oil

Crude oil is a complex mixture of hydrocarbons. The fuel user mainly requires the lighter fuels—petrol, kerosene, diesel oil, gas oil etc. This “end of the barrel” also provides the main feedstock requirement for the petrochemicals and plastics industries. However, the primary separation of crude provides mainly the heavier, more viscous, fuel oils, which potentially cause problems in storage, handling, combustion, and environmental pollution. The main advantage of fuel oil, on the other hand, derives from the fact that these heavier fractions tend to be cheaper. However, offset against this is the need to provide appropriate storage facilities.

Fuel oils are viscous liquids, which become thicker and more intransigent the colder they become. Gas oil, the lightest and least viscous of the fuels, will usually remain in liquid form no matter how cold the winter. This either allows it to flow under gravity from the tank to the burner or enables it to be easily pumped. This holds true unless prolonged periods of cold weather occur and the temperature remains below freezing for a week or more. Under these conditions, some of the waxes contained in the oil begin to form sticky solids. Typically, these solids build up on the filters in the burner supply line, eventually blocking them. Although this is an infrequent occurrence, some exposed sites have installed electric trace heating on the filters and/or the external distribution pipework as a precaution.

The heavier grades of oil require heating in order to remove them from the tank at all. To reduce the amount of energy required for pumping the oil to the burners, an appropriate pumping temperature should be maintained. The oil is heated either electrically or by taking steam from the boiler, thereby reducing its overall efficiency. The uncontrolled overheating of oil can be very expensive and uninsulated or poorly insulated tanks or pipes are also a major waster of energy.

The viscosity, recommended minimum storage temperature, and optimum pumping temperature for the different grades of fuel oil are shown in Table 14.2.

Considerable energy is wasted if all the oil in a tank is heated to the required pumping temperature and it is also bad practice to have too much hot oil circulating and not being used by the burners. A well-designed hot oil ring main circulates sufficient oil plus about 20–30 % in order to meet the maximum demand for all the burners it serves. Fresh oil is drawn from the storage tank as required,

Table 14.2 Characteristics of fuel oils

Type of fuel oil	Grade[a]	Viscosity at 100 °C (cst)	Minimum storage temperature (°C)	Optimum pumping temperature (°C)
Gas oil	D	1.0	None stated	None stated
Light	E	8.2	10	10–12
Medium	F	20.0	25	30–35
Heavy	G	40.0	40	55–60
Bunker	H	56.0	45	70

[a] Refers to BS 2,869–1,986

but the storage never forms part of the basic circulation system, which would allow all the oil to heat up to the pumping temperature. This ensures that both the size and the capital and running costs of the oil heaters are kept to a practical minimum.

The penalty of this oil-heating requirement is that it is uneconomic to use these heavier grades of fuel oil on small boiler plant. Below 3 MW heavy oil would be inefficient and, for bunker oil, 20 MW is probably the lower limit. However, the market price for the heavier fuel oils over recent years has encouraged their greater use.

Provided that a grade of fuel oil is delivered to the burner in good condition and at the correct temperature for the burner, the production of smoke or carbon monoxide should be minimal. The fact that all fuel oils contain some sulfur means that sulfur oxides (SOx) are produced during combustion. Oil, however, burns at a lower temperature than the gaseous fuels and therefore produces less NOx gases.

14.5.4 Coal

The clean burning of coal and other solid fuels present more of a problem because the greater air requirements for their complete combustion. As a result, coal burning has been responsible for most of the traditional forms of air pollution—smoke, soot, grit, and dust. The use of microprocessor control on modern coal plant with improved stoker design has eliminated this problem. Stringent control of SOx and particulates can be achieved through the use of limestone injection, improved cyclones, and bag filters.

Coal is generally the cheapest of the available conventional fuels. Coal-fired plant does, however, incur higher capital and operating costs. As well as the boiler plant itself, the capital cost incurred includes bunkerage, coal handling equipment, and facilities for ash removal, handling, and storage. In general terms, costs for a coal boiler with a conventional stoker can be as high as that of an equivalent oil-fired installation. Operating costs are higher because large coal-fired boiler houses are rarely fully automated and unmanned. Maintenance costs are also significantly higher than for any other fossil fuel.

Coal-fired boilers are rarely, if ever, used in food factories. In addition to the disadvantages cited above, coal storage and handling, and ash disposal, are not compatible with the clean environment associated with food manufacture. For this reason, they are not considered further in this chapter.

14.5.5 Choice of Fuel

The choice of fuel is not a simple matter. It involves balancing a number of factors including the capital cost of the plant, the price of the fuel, and operating and maintenance costs. Some consideration should also be given to likely future changes in fuel and pricing policies and to pollution control legislation. Furthermore, some allowance should be made for the unexpected.

14.6 Gas and Oil Burners

14.6.1 Gas Burners

Apart from the safety requirements in their design, gas burners are essentially simple. Very small boilers use a simple atmospheric burner, which entrains its combustion air from its surroundings. However, as the air and gas are not forced to mix, surplus air is required to ensure complete combustion. This surplus is heated and then passes out via the flue, thereby reducing boiler efficiency. A larger boiler with a fully enclosed combustion chamber needs a burner that will force the air and gas to mix thereby controlling the length and shape of the flame. The quantity of combustion air can be precisely controlled to maximize combustion efficiency.

14.6.1.1 Oil Burners

Oil burners are more complicated because the fuel has to be in the right condition for clean and rapid combustion. This entails atomizing the oil into small droplets of the correct size, which can only be done if it is at the right temperature and therefore the right viscosity. At too low a temperature, the droplets are too big; combustion is poor and produces soot and smoke. At too high a temperature, the droplets can be too small, passing through the flame too rapidly to burn. In both cases, the result is fouling of the heat-exchange surface and inefficient fuel usage.

Oil burners are of three basic types. The simplest and most widely used is the pressure jet where the oil is pumped at pressure through a nozzle. The air or steam blast type uses air pressure to shatter the oil into droplets, while the rotary cup uses centrifugal force to break up the oil. Each type of burner has its advantages and disadvantages (see Fig. 14.2).

All oil and gas burners produced or sold have to meet statutory safety and emission standards.

14.6.2 Burner Controls

In conjunction with the choice of burner type, consideration must be given to the control system required. The simplest *ON/OFF* control means either that the burner is firing at full rate or that it is off. The major disadvantage with this method of control is that the boiler is subject to large and frequent thermal shocks every time the boiler fires. Its use is therefore limited to small boilers with an output up to 300 kW.

Slightly more complex is the *HIGH/LOW/OFF* system in which the burner has two firing rates. The burner operates first at the lower firing rate and then switches to full firing as required, thereby overcoming the worst of the thermal shock. The burner can also revert to the low-fire position at reduced loads, again limiting thermal stresses within the boiler. Typically, this type of system is fitted to boilers with an output of up to 3.5 MW.

A *MODULATING* burner control will alter the firing rate to match the boiler load over the whole turndown ratio. Every time a burner shuts down and restarts the system must be purged by blowing cold air through the boiler passages: this wastes energy and reduces efficiency. Full modulation, however, means that the boiler keeps firing, and fuel and air are carefully matched over the whole firing range to maximize thermal efficiency and minimize thermal stresses. Typically this type of control can be fitted to boilers above 1 MW.

In matching a burner and a control system to a boiler, three factors must be taken into consideration.

Pressure Jet Atomizer

Advantages
- Very simple in construction and cheap to replace.
- Comes in many sizes to suit most applications.
- Can produce all flame shapes from long and thin to short and fat. Hence it can fit all types of boiler combustion chamber.

Disadvantages
- Prone to clogging by dirty oil, which therefore needs to be filtered.
- Limited turndown ratio only 2:1.
- Easily damaged during cleaning.
- Highest pre-heat temperature required for atomization.

Air or Steam Blast Atomizer

Advantages
- Very robust in construction.
- Good turndown ratio of 4:1.
- Good control of the combustion air/fuel ratio over the whole firing range.
- Good combustion of the heavier fuel oils.

Disadvantage
- Energy used either as compressed air or as steam for atomization.

Rotary Cup Atomizer

Advantages
- Good turndown ratio of better than 4:1.
- Good atomization of heavy fuel oils.
- Lowest oil pre-heat temperature required for atomization.

Disadvantages
- Most complex and costly to maintain.
- Electrical consumption for the cup drive.

Fig. 14.2 Advantages and disadvantages of different types of oil burner

- The maximum output of the plant.
- Whether the load is steady or fluctuating.
- The fuel being used.

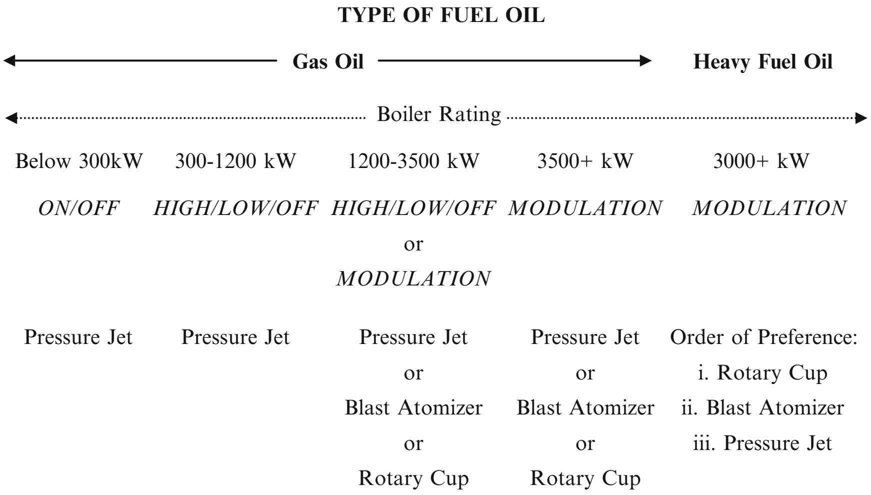


Fig. 14.3 Choice of burner type

An *ON/OFF* control, for instance, is not suitable for heavy fuel oil.

The basic choices as they relate to oil burners are summarized in Fig. 14.3. There is always some overlap between burner types and control system types but the preferred combinations are as outlined.

14.7 Pollution

The three major combustion products, which are potentially damaging to the atmospheric environment, are sulfur compounds (SOx), carbon dioxide (CO_2), and nitrogen compounds (NOx). Although a process for producing low sulfur fuel oils has been in existence for many years, it is expensive: it adds up to 50 % to the cost of a liter of oil and leaves sulfur residues, which have to be disposed of without causing alternative forms of pollution. Limestone, when burned with coal will, however, trap 80 % or more of the sulfur released by the fuel. The sulfur content of natural gas is very small and nearly all of that is deliberately added as the stenching agent.

There are basically two systems for removing sulfur from flue gases: the wet scrubbing method, which washes the SOx out using water; and the dry method of absorbing the SOx on to limestone-type compounds. The wet process produces a dirty acid that has to be disposed of without causing further pollution, and the dry method produces quite large volumes of spent absorber which, again, must be disposed of safely.

Carbon dioxide is inevitably formed as a result of burning any conventional fuel. Again, it could to some extent be removed either by wet scrubbing or by absorption. The current emphasis is on improving overall combustion efficiency so that less fuel is burned: this, in turn, reduces the production of CO_2.

The production of NOx can be restricted by the correct design of the combustion system. The most significant problem occurs with those fuels having the highest flame temperatures, i.e., fuel oil and gas. A great deal of research has gone into developing low excess air burners which have been shown to limit NOx production.

The Environmental Protection Act (1990) set out future UK policy concerning emission of the various gases contributing to the greenhouse effect. The stated objective for the first 10 years was to stabilize the emission of such gases at the 1990 level despite an expected rise in demand over that same period. Plant manufacturers have therefore been compelled to incorporate new standards into their designs. However, it is not enough for a boiler operator merely to have bought plant that meets the new standards; he has to demonstrate that it achieves those standards in day-to-day operation.

Current UK legislation (as at January 2012) divides boiler plant into three categories:

1. Plant with a net-rated thermal input below 20 MW.
2. Non-aggregated plant with a net-rated thermal input between 20 and 50 MW.
3. (a) Aggregated plant from 3 MW minimum with a net-rated thermal input above 50 MW but below 500 MW (b) Aggregated plant with a net-rated thermal input exceeding 500 MW.

Category 1 boilers are covered by the Clean Air Act 1993 (available online at www.legislation.gov.uk) and are controlled by the Local Authority. Those within Category 2 are covered by the Environmental Protection Act 1990 (also available online at www.legislation.gov.uk) and are again controlled by the Local Authority. For additional information, see DEFRA (1995) and DEFRA (2004). Category 3 boilers are covered by the Environmental Protection Act and are controlled by the Environment Agency. For guidance, see Environment Agency (2009).

14.8 Steam

14.8.1 Raising Steam

14.8.1.1 Basics

To change water into steam, the water temperature must be raised to its boiling point (saturation temperature) by adding sensible heat. Latent heat is then added to turn the water into steam. For a kettle operating at atmospheric pressure, 419 kJ/kg (180 Btu/lb) of sensible heat would be needed to raise the water temperature from freezing point, 0 °C (32 °F) to boiling point, 100 °C (212 °F). To convert 1 kg (2.2 lb) into steam a further 2,258 kJ (970 Btu) are required. It is this large quantity of latent heat that is recovered by the process at the point of use.

If the pressure is increased the water will no longer boil at 100 °C but at a higher temperature. The total heat content of steam increases with pressure: however, the useful latent heat content decreases as more of the input energy is required as sensible heat. This property of boiling at higher temperatures as the pressure is increased allows the process temperature requirement to be exactly matched. If, for example, a material being processed undergoes a certain chemical change at 170 °C, a pressure of at least 7 bar will be required. At this pressure less latent heat is available from each kilogram of steam so, proportionately more steam is required.

14.8.1.2 Steam Purity

Steam purity is influenced by a range of operational factors, including steaming rate, boiler pressure, steadiness of steam demand, and water level. Another factor is the composition of the boiler feed water. Control of total solids, alkalinity and suspended solids is necessary to avoid foam production and a subsequent increase of carry-over. Organic detritus, oil or surface-active agents also cause foaming. Anti-foams can be used to correct situations where the boiler requirements are being met but foaming and carry-over are still being experienced. In some circumstances, the anti-foam can be used to allow further concentration of the boiler water and thus reduce the amount of blowdown required. However, care should be taken to avoid exacerbating deposition and corrosion problems.

Other sources of steam contamination are boiler water carry-over, volatilization of compounds in the boiler water, process leaks and other steam-side failures.

Contaminated steam may cause deposition in heat exchangers, control valves and other equipment, process contamination and loss or impairment of product in direct steam injection and contaminated condensate that cannot be reused in the feed system. In high-pressure boilers, silicate becomes more soluble in steam and may deposit on equipment downstream of the boiler. Water carry-over can also cause corrosion.

14.8.1.3 Steam Distribution

For optimum performance of steam-using equipment, a supply of steam at the right quantity and quality is vital. To meet the quality requirement, steam must be at the correct pressure to satisfy process temperature requirements. Efficient use of heat exchange equipment normally dictates the use of saturated steam.

An ideal steam distribution system would take the shortest possible route from the boiler to the process and use the smallest possible pipe. The first criterion is obvious because, no matter how well insulated the pipework, its contents are at a high temperature and heat losses will occur. The second criterion minimizes heat losses but increases the pressure drop and frictional losses within a system.

The final design of a practical steam distribution system is necessarily a compromise between this ideal and several other factors. Factors to be considered when designing a new steam distribution system or when assessing an existing one are outlined further on in this section. Lack of attention to these will significantly increase operating costs, either because of reduced overall efficiency or because of increased maintenance costs.

14.8.2 Steam Pressure

Steam should be generated at the pressure necessary to meet the maximum required by the equipment in the system. In practice, the pressure chosen offers a balance between capital costs and the overall energy efficiency of the system. The benefits of distributing at high pressure are as follows:

- High-pressure distribution minimizes the size of pipe required. As the pressure increases, the specific volume of steam decreases. A smaller diameter pipe means that capital costs are reduced.
- High-pressure distribution minimizes the amount of insulation required as the pipe diameter is reduced. However, this benefit is not always achieved as, with increasing steam temperature, the minimum recommended insulation thickness increases.

Set against these advantages is a number of other factors.

- The possibility exists of having to use thicker-walled, more expensive pipework at the higher pressure. This will also apply to all fittings, such as flanges, etc.
- Steam leakage losses are higher. As a general statement, leakage losses increase in proportion to the pressure. They are twice as much at 10 bar as at 5 bar.
- The potential for producing flash steam increases and this goes to waste unless a low- pressure sink can be operated in parallel with the high-pressure equipment.

- Heat losses are higher. They increase approximately in proportion to the steam saturation temperature, e.g., heat loss per square meter at 10 bar is some 15 % more than at 5 bar. This must be set against the benefit of the smaller-diameter pipework.
- Steam reduced in pressure via a pressure-reducing valve (PRV) may have to be desuperheated before being used in a process. When the pressure of saturated steam is reduced, the heat content is not lost. The excess heat above that which the saturated steam at the new pressure can hold turns into sensible heat in the steam, thereby raising its temperature. In cases where maximum temperature is a critical process parameter this excess heat must be removed and may be lost to the system, thereby reducing its overall efficiency.

Determining the pressure for small distribution systems is relatively simple; it should just meet the minimum user requirements unless future expansion of the system or new equipment requiring higher pressures is envisaged.

For systems where only a small quantity of high-pressure steam is required but where large quantities of low-pressure steam are used, the possibility of separating the two should be considered. A high-pressure steam generator dedicated to the high-pressure steam using equipment could be a more energy efficient option.

14.8.3 Pipe Sizing

Once the necessary system pressure has been determined, the pipes must be correctly sized. If the pipe is too small, insufficient steam at a high enough pressure will get through to the process. Too large a pipe simply means that surface heat losses are increased. Either way, the overall system efficiency drops. Proper sizing of the steam lines means selecting a pipe diameter, which gives the minimum acceptable pressure drop between the boiler and the user.

For many years designers and engineers used simple "rule of thumb" methods to determine the pipe sizes for a particular application. These criteria were evaluated from actual situations and generally still hold good. The simplest method involves calculating the steam velocity in a pipe for a given flow rate. The only information required is the specific volume of the steam for the chosen distribution pressure, and this can be obtained from steam tables. The only other factor that needs to be known is the quality of the steam, whether it is wet or superheated. Wet steam contains water droplets, which can cause damage and erosion when they hit the pipe walls at bends or at valves and fittings. Superheated steam contains no water droplets, and none are likely to condense out in the pipe; the danger of water droplet damage is therefore negligible and higher pipeline velocities can be used. The practical guidelines are as follows:

- Superheated steam velocity—50–70 m/s.
- Saturated steam velocity—30–40 m/s.
- Wet or exhaust steam velocity—20–30 m/s.

Over the years a number of charts and nomographs have been published for evaluating the pressure drops within a steam distribution network. In all cases, even for those methods now available as a computer program, the results obtained fall within the velocity bands given above. The only exceptions would be for very low-pressure steam (less than 1 bar) and for very high-pressure steam (above 20 bar). This section has been aimed at typical industrial and commercial applications where steam pressures are usually between 3 and 17 bar.

As stated earlier, other reasons for maintaining pipework diameter at the minimum are the capital cost and the surface heat losses. Using a 75 mm (3 in.) diameter pipe instead of a 50 mm (2 in.) pipe increases the capital cost of the pipe and its insulation by approximately 50 %, i.e., in direct proportion to the pipe diameter. The heat losses from the pipe are also directly related to the outer surface area which means that they are also 50 % greater for an equivalent increase in pipe size.

14.8.4 Drain Points and Layout Guidelines

The fact that steam is produced from water, which is relatively cheap and plentiful, is a definite advantage. The fact that, as steam cools it reverts to water, is not. Condensate in a steam line is at least a nuisance but can be potentially disastrous. At the very least, condensate lying in the bottom of a pipe effectively reduces that pipe's cross-sectional area so requiring increased velocities and causing a higher pressure drop.

In the worst case, the condensate layer becomes deep enough to be picked up by the steam and forced as a bullet or plug down the pipe. These high velocity slugs have difficulty passing round bends and through fittings. In extreme cases this *water hammer* effect can lead to sudden failure of the pipe or of fittings such as valves.

There is also a possibility of damage if the condensate is carried forward into the process units. Wet steam builds up a thick film on heat transfer surfaces, reducing their effectiveness. It also leads to excessive erosion and wear on the pipework and fittings, thereby increasing maintenance costs. The excess condensate has to be removed by the existing steam traps, possibly overloading them and leading to early failure.

Good steam pipework layout ensures that there is provision for removing condensate from the distribution system before it can cause a problem. For this provision to be effective the pipes must be installed so that the condensate flows towards these drain points.

General guidelines for the effective draining of condensate and layout of steam lines are given below.

- The steam main should be laid with a falling slope in the direction of the steam flow of not less than 125 mm for every 30 m of pipe length. This ensures that the condensate always flows to the point at which the next drain point is sited.
- Drain points should be provided at intervals of 30–40 m along the steam main. The actual distances will vary, depending on how often a branch pipe occurs and how often there is a change in the level or direction of the steam main. In a straight run of pipe carrying dry steam, drain points and steam traps should be 45 m apart. Installing them at more frequent intervals increases the possibility of failure and steam venting. If the steam produced by a boiler plant is very wet, the drain points and trap sets must be at more frequent intervals.
- Condensate will always collect where there is a low point in the system, so a drain point is required at all such locations. At any bend there is an increased likelihood of entrained condensate droplets being deposited on the walls of the pipe; this is especially true where a steam main rises. A drain point here is therefore required.
- A sump should be provided at drain points in the main steam lines. The simplest method is to use an equal "T" connection, the bottom limb forming the sump.
- The choice of steam trap is important for the main steam lines. Open bucket traps or thermodynamic (TD) traps should be used where possible.
- Branch lines should always be connected at the top of the steam main. This largely prevents any carry-over of condensate into the branch.
- Pipework and insulation are heavy. If the pipe is not adequately supported at regular intervals sagging will occur. This creates low points for the build up of condensate. The type and frequency of the support required will depend on the diameter and wall thickness of the pipes.
- Steam pipework does not remain at working pressure and temperature all the time. At start-up and shutdown the metal of the pipework expands and contracts. If no allowance is made for this movement, a considerable amount of stress is set up which can lead to cracking and ultimate failure. To overcome this problem, expansion loops with smooth swept bends are installed at intervals in the steam main. Smaller steam mains and branches may also require expansion allowance: in these cases bellows-type expansion joints are commonly used.

- All steam-using equipment operates best with dry steam but for some equipment dry steam is essential.
- Steam separators or dryers, as their name implies, remove the entrained droplets of water from the steam. These should be installed before essential equipment and, again, should be properly drained and trapped.

14.8.5 Efficient Steam Trapping and Venting

14.8.5.1 The Steam Trap

The expression “steam trap” has already been used a number of times. A steam trap is a device that fulfils three important functions.

- It removes the condensate formed either within the steam pipework or within the process equipment. It must be able to do this at least as quickly as the condensate is formed or the system will become waterlogged. In the case of the steam lines, this would lead to water hammer and the risk of damage to pipework and fittings. In process equipment, waterlogging means that the steam cannot get in to heat up whatever requires heating, therefore the process stops or at least slows down significantly.
- As its name suggests, one of the functions of a steam trap is to prevent large amounts of steam escaping. However, some traps require small amounts of steam to escape in order to operate correctly.
- A steam trap should enable any noncondensable gases in the system to escape. If the gases remain they will take up part of the space that the steam should occupy: this reduces the carrying capacity of the pipework and prevents the steam reaching the heat transfer surfaces of process equipment. In the worst case a pipe or piece of equipment can become air-locked so that even the condensate cannot be released. Moreover, the presence of even small quantities of air in steam significantly inhibits heat transfer.
- The gases that must be removed comprise first the air that fills the system when it is cold and drained down. In addition, during normal operation, some noncondensable gases can get into the system either by being dissolved in the feedwater or as a result of a breakdown of chemicals in the feedwater.

14.8.5.2 Trap Testing

Trap testing should be carried out in a regular and systematic manner. Several methods of testing may be employed, such as checking for high temperature at the inlet, installing sight glasses at outlets or using ultrasonic detectors. Traps are now available incorporating sensing devices, which can easily be checked manually or included within a computer-based monitoring system.

14.8.5.3 Group Trapping

Where possible, each item of process equipment or pipeline should have a separate steam trap. Group trapping, which involves taking the discharge lines from a number of steam spaces and discharging the condensate through a single trap, often leads to problems. The system must be correctly designed, sized and installed to cope with what may be an extremely variable load. Two important factors must be considered.

- The type and size of trap must be capable of handling the variable load. This will obviously range from the situation where only one plant item is on load to the start up situation with every connected item discharging to the trap. This variability will increase wear on the trap, necessitating more frequent maintenance or replacement.
- When two or more units, each with different operating characteristics, are connected together, it is not unusual for one unit to exercise a back pressure on another unit, preventing it from discharging condensate. In the extreme case one or more units can become partly or wholly waterlogged making them inefficient in transferring heat. The installation of check valves does not overcome the problem: the solution is correct pipeline sizing.

14.8.5.4 Strainers

Steam pipelines are prone to internal corrosion. Inevitably scale and dirt from the pipework, etc., breaks off and is carried forward. Scale and dirt are one of the simplest reasons for steam trap failure. Large flakes of scale can readily be removed by installing a short drop leg in the piping before the trap. Small particles of dirt, however, can only be removed effectively by a fine mesh strainer installed in front of each trap. Once a strainer is installed it will require cleaning. The frequency of cleaning will vary considerably from site to site and will depend on the type of boiler installed, the type of water treatment regime used, the age of the pipework and the overall operating conditions.

14.8.5.5 Air Venting

Proper air venting is a must for all steam consuming equipment to ensure effective heat transfer. The presence or build up of air occurs because of the partial vacuum created in pipes and equipment during shutdown. The provision of properly sized and installed air vents ensures that trapped air is quickly removed. As mentioned above, the trapped air or gases prevent the steam from occupying that space, thereby restricting heat transfer. This most frequently causes a problem during start-up when the greatest volume of air must be discharged. Any inadequacy in air venting manifests itself in an increased heat-up time. The temperature sensitive air vents must open up to allow air and gases, but not steam, to vent.

Air vents discharge air full-bore during start-up but open up during operation only when air and other gases collect. Such automatic air vents are preferred to hand operated vents. Even in the best run establishments, vents are often forgotten, never used or left partially open. The location of air vents should be where the greatest volume of air is likely to collect. This is normally near the top of the steam space and in the condensate line.

14.8.6 Condensate Return Systems

14.8.6.1 The Importance of Condensate Recovery

Steam condenses after giving up its latent heat to the process being heated. The condensate contains a sizeable proportion of the original heat content supplied by the fuel—around 20 %. It is wasteful to throw this away so either an alternative use for it must be found in another process or it must be retained within the steam system. Condensate that has not been in direct contact with the process is chemically pure and therefore needs little water treatment apart from pH adjustment. Both water treatment costs and blowdown losses can therefore be reduced.

Experience from many industrial and commercial sites has shown that much less importance is given to the condensate recovery system than to the steam system. All too often condensate is not returned to the boiler house and is discharged to drain. Investment in condensate recovery systems including pipes, valves, transfer pumps, insulation, etc., has, on many occasions been shown to produce quick returns.

There are some exceptions, usually associated with large-scale sites where the capital cost of installing and operating condensate collection is prohibitive. One such exception usually occurs where there is a relatively small load a long way from the boiler house. Another exception is where the length of pipe run, even when well insulated, is so long that there would be no useful heat content left in the condensate at the boiler house. In some cases, however, it may still be economic to return cold condensate over long distances because of the high cost of raw water and feedwater treatment.

Even when it is uneconomic to return the condensate to the boiler house, its energy content should not be discarded unless there is no alternative. The heat content of condensate can, for example, be used either directly or indirectly for process hot water generation.

Unfortunately, the condensate can sometimes become contaminated by contact with some other substance being processed. Contaminated condensate, if returned to the boiler, often results in fouling of the heat transfer surfaces, thereby reducing efficiency. In the worst cases, catastrophic failure of the boiler can result from overheating of the metal as a result of this fouling. Frequently, the amount of contaminated condensate is small and does not justify the expense of buying and maintaining heat recovery equipment. In those exceptions where the quantities are significant and where there is a use for process hot water, a simple heat exchanger can be used to avoid wasting the energy involved. It must be remembered, however, that the heat exchanger will also suffer from fouling by the contaminated condensate, but regular cleaning should be simpler to arrange in this situation.

The one rule that must apply, and which overrides all considerations of energy conservation, is that wherever there is any doubt as to the purity of the condensate it *must not* be reused as boiler feedwater.

14.8.6.2 Pipe Sizing

It is just as important to ensure that the correct size of pipework is installed for the condensate as it is for steam, and for basically the same reasons. If the pipe is too small, more energy is needed to overcome the back pressure generated within the system, i.e., condensate pumps will need to generate higher heads. If the pipe is oversized the installation cost will be higher and the surface heat loss greater.

Accurate sizing of condensate pipework is much more difficult than the equivalent for steam. Under normal operating conditions some of the condensate will “flash” to steam in the pipework. The proportion involved is normally small in weight but occupies a relatively large volume, and an understanding of this form of two-phase flow is required when determining the correct pipe size.

Fortunately years of practical experience have produced a “rule-of-thumb”: all condensate pipework should be sized for water flow under start-up conditions. Under these conditions steam condenses rapidly and the consumption will be at least twice that of normal operation. Experience has shown that pipes sized in this way will be adequate to carry the mixed flash steam and condensate under operating conditions. Pipe sizing is normally based on a pressure drop of 0.8 mbar per meter run of pipe.

The rule-of-thumb only applies for steam system pressures up to 14 bar. At higher pressures the quantity of extra flash steam occurring in the pipework is much greater and requires the condensate pipework to be even more generously sized. The best way of dealing with the additional flash steam occurring in high-pressure systems is to recover it at a lower pressure and use it elsewhere within the process. The alternative is to install a closed pressurized condensate return system. Such systems are, however, expensive to install because every piece of equipment must be able to withstand the high pressures involved. Furthermore, many components within such a system are in essence pressure vessels and, as such, are subject to insurance inspection

14.8.6.3 Layout

In a well-designed system, the condensate return will not impose an unreasonable back pressure on the steam traps. This is essential, especially during start-up when the traps have to vent first large quantities of air from the system and then large volumes of water.

It is rarely possible to gravity feed condensate back to the boiler feed tank. It is conventional to install condensate receivers at low level, thereby minimizing the back pressure on the steam traps, and then to pump the condensate back to the boiler house. Either electric pumps or an automatic pumping trap can be used. Whichever is selected, it must be able to cope with condensate that is near its boiling point. All condensate-collecting vessels should be properly vented as they are not manufactured as pressure vessels and cannot withstand full steam pressure when a trap fails.

14.8.6.4 Lifting Condensate

All good reference books state that condensate should never be lifted from a low-level outlet to a high level collecting vessel or pipe. In practice, however, often the only convenient place to install condensate pipework is at high level. When lifting condensate a check valve is essential.

The steam pressure at the trap has itself to be used to lift the condensate. The condensate exerts a back pressure of 1 bar for each 10 m of lift. This in turn reduces the pressure differential across the trap, which means that it can pass less condensate. If a trap has to lift condensate 10 m from a vessel with steam at 3 bar, it can only pass approximately 65 % of the amount it would pass if the condensate were to be discharged to atmosphere. To overcome this problem larger traps must be used.

14.8.6.5 Flash Steam Recovery

Flash steam is produced when condensate at a higher pressure is released to a lower pressure. The recovery of flash steam from high-pressure condensate is an important heat saving opportunity. The condensate leaving a steam trap is at substantially the same pressure as the steam. For example condensate at 5 bar will be at 159 °C and contain 671 kJ/kg of sensible heat. As water at atmospheric pressure can only hold 419 kJ/kg, the extra 252 kJ is used to re-evaporate some of the water to produce flash steam. The flash steam is produced from condensate released by a steam trap.

Appendix

Boiler Feed Water Additives

Boiler water additives may be safely used in the preparation of steam that will contact food, under the following conditions:

(a) The amount of additive is not in excess of that required for its functional purpose, and the amount of steam in contact with food does not exceed that required to produce the intended effect in or on the food.

(b) The compounds are prepared from substances identified in paragraphs (c) and (d) and are subject to the limitations, if any, prescribed.

(c) List of substances:

Acrylamide-sodium acrylate resin[a]
Acrylic acid[a]
Ammonium alginate
Cobalt sulfate (as catalyst)
Lignosulfonic acid
Monobutyl ethers [a]
Poly(acrylic acid-co-hypophosphate) sodium salt[a]
Polyethylene glycol[a]
Polymaleic acid[a]
Polyoxypropylene glycol[a]
Potassium carbonate
Potassium tripolyphosphate
Sodium acetate
Sodium alginate
Sodium aluminate
Sodium carbonate
Sodium carboxy-methylcellulose[a]
Sodium glucoheptonate[a]
Sodium hexametaphosphate
Sodium humate
Sodium hydroxide
Sodium lignosulfonate
Sodium metabisulfite
Sodium metasilicate
Sodium nitrate
Sodium phosphate (mono-,di-,tri-)
Sodium polyacrylate
Sodium polymethacrylate
Sodium silicate
Sodium sulfate
Sodium sulfite (neutral or alkaline)
Sodium tripolyphosphate
Tannin (including quebracho extract)
Tetrasodium EDTA
Tetrasodium pyrophosphate

[a] See FDA (FDA 2011) for limitations

(d) Substances used alone or in combination with substances in paragraph (c) of this section:

Cyclohexlamine[a]
Diethylaminoethanol[a]
Hydrazine[a]
Morpholine[a]
Octadecylamine[a]
Trisodium nitrilotriacetate[a]

[a] See FDA (2011) for limitations

(e) To ensure safe use of the additive, in addition to the other information required by the Act, the label or labelling shall bear:

- The common or chemical name or names of the additive or additives.
- Adequate directions for use to ensure compliance with all the provisions of this section.

Acknowledgment The author wishes to thank the Energy Technology Support Unit, ETSU (now incorporated into Future Energy Solutions, Harwell) for permission to reproduce information.

References

DEFRA (1995) "Environmental Protection Act 1990, Part 1. Secretary of State's guidance – Boilers and furnaces, 20–50 MW net rated thermal input", Department of the Environment, August, Available online at http://archive.defra.gov.uk/environment/quality/pollution/ppc/localauth/pubs/guidance/notes/pgnotes/documents/PG1_03.pdf.

DEFRA (2004) "Amendment of PG 1/3 (95) Boilers and furnaces, 20–50 MW net rated thermal input", Department for Environment Food and Rural Affairs, 6 October. Available online at http://archive.defra.gov.uk/environment/quality/pollution/ppc/localauth/pubs/guidance/notes/aqnotes/aq23%2804%29.htm.

Environment Agency (2009) "How to comply with your environmental permit. Additional guidance for combustion Activities", Environment Agency, March. Available online at http://publications.environment-agency.gov.uk/PDF/GEHO0209BPIN-E-E.pdf.

FDA (2011) "Boiler water additives", US Food and Drug Administration, Code on Federal Regulations Title 21, Section 173.310, 1 April. Available online at http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?fr=173.310.

Malek, M.A. (2005) "Power boiler design, inspection and repair: ASME code simplified", McGraw-Hill, New York, 629 pp.

Woodruff, E.B., Lammers, H.B. and Lammers, T.F. (2005) "Steam plant operation", 8th edit., McGraw-Hill, New York, 850 pp.

Chapter 15
Refrigeration Systems

S.J. James

15.1 Introduction

Developments in frozen storage in the last century established the international food market. Further developments in temperature control for chilled products have led to the rapid expansion of the "fresh" food market. Refrigeration is the most common form of food preservation and has considerable further potential. The International Institute of Refrigeration (IIR) estimates that 240 MT of food is refrigerated throughout the world. They believe that at least 1,800 MT of food would benefit from refrigeration in its production and distribution.

Refrigeration stops or reduces the rate at which changes occur in food. These changes can be biochemical (growth of microorganisms), physiological (e.g., ripening, senescence, and respiration), chemical and enzymatic (e.g., browning reactions, lipid oxidation, and pigment degradation), and physical (such as moisture loss).

Effective refrigeration produces safe food with a long, high-quality shelf life. This chapter describes some of the refrigeration systems available for food use. It then considers some new or novel refrigeration systems and finishes with a very important section on specifying, designing, and optimizing refrigeration systems.

15.2 Types of System

A range of different refrigeration systems is available for food use. The most common are based on refrigerated air. Others rely on sprays, immersion, plate or vacuum cooling technology.

15.2.1 Air

Air is by far the most widely used method of both chilling and freezing food since it is economical, hygienic and relatively noncorrosive to equipment. Systems range from the most basic in which a fan

---

S.J. James (✉)
Food Refrigeration and Process Engineering Research Centre (FRPERC), The Grimsby Institute (GIFHE),
HSI Building, Origin Way, Europarc, Grimsby, North East Lincolnshire DN37 9TZ, UK
e-mail: jamess@grimsby.ac.uk

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_15,

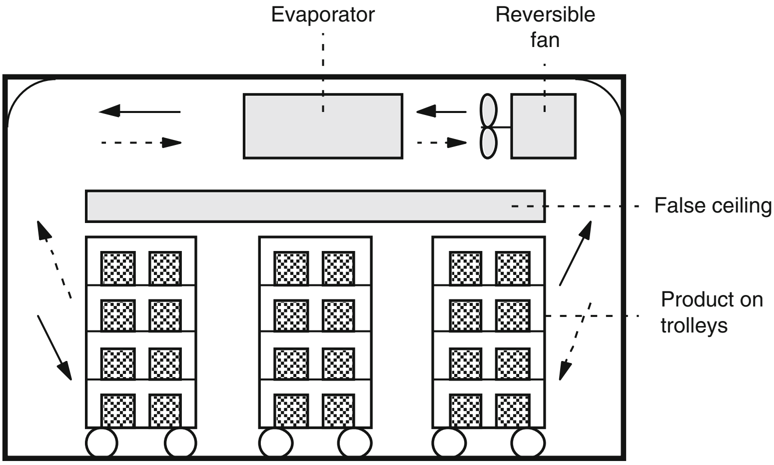


Fig. 15.1 Simple chilling or freezing tunnel with longitudinal air circulation

draws air through a refrigerated coil and blows the cooled air around an insulated room (Fig. 15.1) to purpose-built conveyorized blast chilling tunnels or spirals. Relatively low rates of heat transfer are attained from product surfaces in air systems. Their big advantage, however, is their versatility, especially when there is a requirement to cool a variety of irregularly shaped or individual products.

In practice, air distribution is a major problem, often overlooked by the system designer and the operator. The cooling time of the product is reduced as the air speed is increased. However, the power required to drive the fans increases correspondingly. As a result, there is an optimum air speed, which should be employed in each case to achieve lowest-cost operation. This optimum value can be as low as 1.0 ms^{-1} when cooling large carcasses to 15 ms^{-1} plus for thin products.

One of the major considerations affecting the quality of air-chilled and frozen products is the degree of moisture loss from unwrapped product surfaces to the refrigerated air. Loss of surface moisture leads to a poor appearance in many products. Equally important is the loss of revenue arising from the reduction in weight of the final product. The difference in temperature between the refrigerated air and product surface is the primary driving force for moisture removal. Thus, most of the moisture loss occurs in the initial stages when the surface temperature is high. In general, weight loss is minimized by employing rapid chilling or freezing cycles, using low air temperatures and high air speeds.

15.2.1.1 Batch Systems

Placing warm food items in large insulated refrigerated rooms is the most common method of cooling. Fans circulate air through refrigerated coils and around the products. Large individual items such as meat carcasses are hung from overhead rails; smaller products are placed either unwrapped or in cartons on racks, pallets, or in large bins.

In a simple, single-stage batch chilling system, the risk of surface freezing limits the lowest air temperature that can be used. This problem is further complicated if products with different thermal properties and/or sizes are cooled at the same time. For example, two-compartment ready meal consumer packs typically contain rice or pasta in one compartment and a meat- or fish-based product in the second. The components have very different thermal properties and may be filled to different depths.

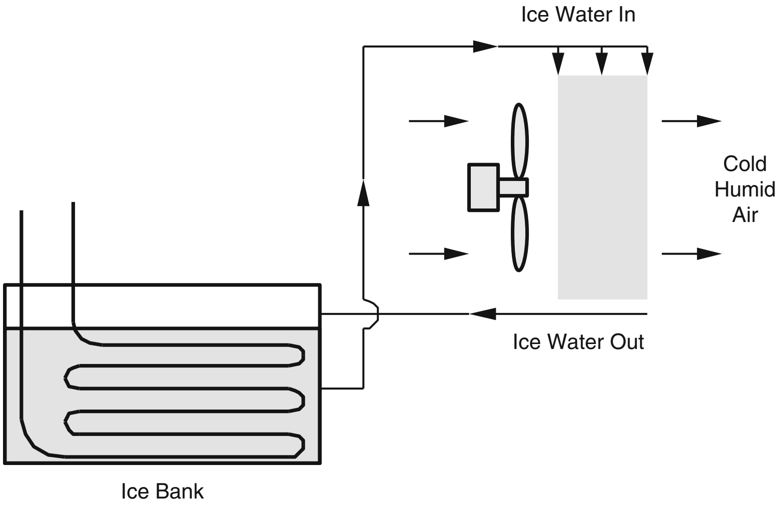


Fig. 15.2 Diagram of a wet air chiller utilizing an ice bank refrigeration system

15.2.1.2 Continuous Systems

Product is conveyed through a chilling tunnel or refrigerated room usually by an overhead conveyor or on a belt. This overcomes the problem of uneven air distribution since each item is subjected to the same velocity/time profile. Some cooked products are continuously chilled on racks of trays (2.5–5 m high), pulled or pushed through a chilling tunnel by mechanical means. This does, however, involve double handling and it is difficult to achieve an even air distribution through the layers. For larger operations, it is more satisfactory to use linear tunnels or spiral chillers. Linear tunnels are of simpler construction but are restricted by the length of belt necessary to achieve the cooling time required and by the space available in most factories. Spiral chillers are therefore a more viable alternative. Fluidized bed freezers are also used to process small unwrapped individually quick frozen (IQF) products having a relatively small and uniform size. Examples include certain fruit and vegetables

15.2.1.3 Wet Air/Ice Bank Cooling

As noted above, one of the principal disadvantages of air-cooling systems is their tendency to dehydrate unwrapped product. A way around this problem is to saturate the air with water. Wet-air cooling systems (Fig. 15.2) recirculate air over ice-cold water so that air leaving the cooler is cold (0–1 °C) and virtually saturated with water vapor (100 % RH). An ice bank chiller is a common way of producing the cold water employed. In such systems, ice is built up around the evaporator (plate or coil), which is immersed in a tank of water. Water is circulated over the coil and then through a packed bed. Air circulating through the bed is cooled and humidified.

As well as the economic advantage of reduced weight loss, the operation of ice bank chillers offers a number of economic savings over conventional air chillers. These are:

1. The size of refrigeration plant required for an ice bank chiller is smaller since peak heat loads are met by the reserve of ice. The plant therefore runs for longer periods at full capacity.
2. Running a refrigeration plant at full load (as ice bank systems operate) is more efficient than running at part load. Therefore the overall efficiency of the chilling operation is greater.
3. A smaller plant consumes less power.

4. Part of the cooling capacity is used to build up a reserve of ice during the period between midnight and 7.00 a.m. During this time electrical power is approximately one-third of the daytime cost.

A principle disadvantage of ice bank coolers is the space required. For example, a chiller holding 800 pigs of average weight 45 kg would require 2,000 kg of ice occupying approximately 4.0 m^3. Also, as with immersion systems, wet air produces wet product surfaces that may detract from the appearance, make handling difficult, or provide an enhanced environment for microbial growth.

Wet-air cooling has been used commercially for some 25–30 years, principally for the pre-cooling and storage of vegetables and fruit. Other applications remain to be exploited.

15.2.2 Spray/Evaporative Chilling

This system is mainly used to chill poultry, although research has demonstrated the potential for use with other products. After soft scalding, the carcasses are transferred to an air chiller and sprays of potable water applied at periodic intervals. Weight loss is greatly reduced and there is little if any water uptake. In the Netherlands today, evaporative chilling has replaced nearly all immersion chillers. Spraying with ambient or chilled water is an effective method of initially cooling cooked products that can withstand wetting, such as hams and sausages.

15.2.3 Immersion

In an immersion system, the product is immersed in or sprayed with water, either at ambient temperature or near 0 °C. The water is normally treated with a mild disinfectant such as chlorine or a phenol-based compound. Practical systems vary from simple stirred or unstirred tanks to more complex plants where products are conveyed through agitated tanks or under banks of sprays.

Most frozen poultry is initially chilled by immersion in chilled water or ice–water mixtures. There is, however, water uptake during the process and methods for measurement and control of weight gain are prescribed by EEC Regulation 2967/76; see EEC (1976), EEC (1980). The process used is normally a counterflow system in which the birds are conveyed in the opposite direction to the water flow in order to minimize cross-contamination.

15.2.4 Contact (Plate, Belt, Drum)

Contact refrigeration methods are based on heat transfer by contact between products and metal surfaces, which in turn are cooled by either primary or secondary refrigerants. Contact freezing and chilling offers several advantages over air cooling, i.e., much better heat transfer and significant energy savings. However, the need for regularly shaped products with large flat surfaces is a major hindrance.

These systems can be broadly classified into three main groups: plate, belt (band), and cylindrical (drum). Cylindrical freezers (scraped-surface heat exchangers) are generally employed for freezing liquid products. In the large-scale production of ice cream, for example, the aerated mix is cooled to between −4 and −7 °C in the exchanger. The product is a frozen slurry, which still flows readily and can be packaged prior to final freezing in a hardening room.

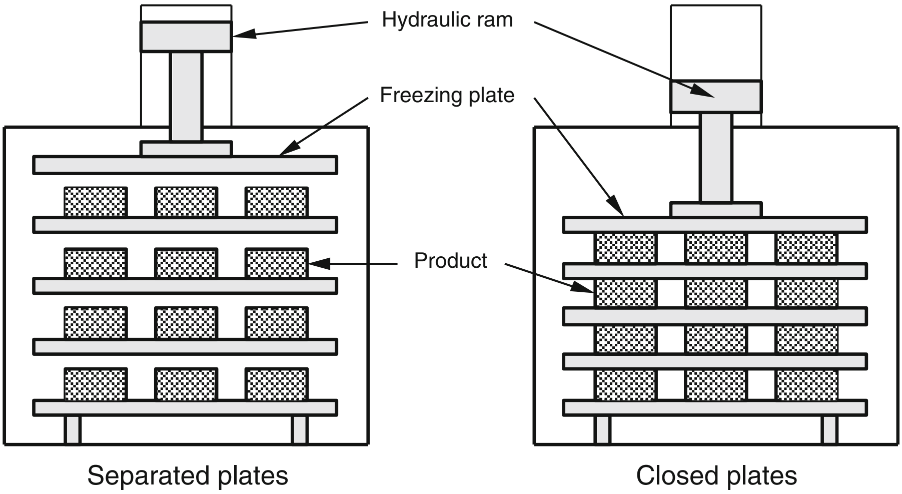


Fig. 15.3 Schematic of horizontal plate freezer/chiller

Modern plate cooling systems differ little in principle from the first contact freezer patented in 1929 by Clarence Birdseye. Essentially, the product is pressed between hollow metal plates containing a circulating refrigerant (Fig. 15.3). A hydraulic cylinder is used to bring the freezing plates into pressure contact with the product. These plates can be either horizontal or vertical.

Freezing time is dependent on product thickness, contact effectiveness and the conductivity of the product. Plate freezers are often limited to a maximum thickness of 50–70 mm. Good contact is a prime requirement. Air spaces in packaging and fouling of the plates can have a significant effect on cooling time.

General advantages of plate freezers over air-blast carton freezers include:

1. Freezing is either faster for the same refrigerant evaporating temperature, or can take place at a higher evaporating temperature for a given freezing time.
2. Product temperatures are easier to control, especially for smaller cuts.
3. Power consumption is significantly reduced—savings of at least 30 %, and possibly 50 % or more, may be expected because air-circulating fans are not required and because higher evaporating temperatures can be used for the same effective cooling-medium temperature.
4. In many cases, less building space is required.
5. The product remains uniform and flat after freezing, unlike air-blast frozen cartons, which often bulge. The flat cartons result in stable loads, giving up to 30 % higher space utilization in cold stores. For transport, the stable pallets facilitate unitized loading, and some 8–10 % more product can be loaded into a container.

Disadvantages of plate freezers relate mainly to cost:

1. Capital costs are significantly higher than for equivalent air-blast freezers. Manually loaded plate freezers are comparable in cost to automatic air-blast tunnel freezers. Fully automatic plate freezers are more expensive.
2. High circulation rates of liquid refrigerant are required. This results in additional costs for larger accumulators and higher capacity pumps.
3. For manual plate freezers, simultaneous loading and unloading may require higher labor input than for a batch air-freezer.
4. Each plate must be loaded with product of the same thickness.

Table 15.1 Predicted freezing time of meat blocks in a plate freezer operating at −30 °C

	Freezing time (h)		Cycles per day	
Thickness (mm)	Cartoned	Bare	Cartoned	Bare
80	6.3	2.5	3	6
160	16.5	8.5	1	2

Table 15.2 Predicted cooling times from 40 to 2 °C at the center of meat slabs in various cooling systems

	Meat thickness (mm)		
Cooling method (operating at −1 °C)	20	40	80
Air (still)	5.0 h	11.0 h	24.0 h
Air (5 ms^{-1})	1.2 h	2.8 h	7.4 h
Plate	0.7 h	1.8 h	5.5 h
Immersion	0.4 h	1.2 h	4.4 h

5. Damp cartons can stick to plates or cause jams when ice forms.
6. Air infiltration must be minimized to prevent frost build up on plates.

Freezing unpacked meat has significant advantages because of the substantially shorter freezing times. Twice as many freezing cycles per day can be achieved with the bare product (Table 15.1). These freezing systems could readily be modified to operate at higher temperatures for chilling operations. With thin materials, a plate chilling system has the potential to halve the cooling time required in an air blast system (Table 15.2).

15.2.5 Vacuum

Vacuum cooling is mainly applied to solid products having large surface area to volume ratios and an ability to readily release internal water, and to liquid or solid–liquid mixtures. Pie and pastry fillings and components of ready meals are commonly cooked in large heated vats under elevated pressure, and then cooled (often in the same vats) under reduced pressure. Products are placed in a sealable chamber, which is then evacuated to a pressure of typically 500–700 Pa. At reduced pressure, water readily evaporates from the surface of the product and, as it does so, the latent heat of evaporation is extracted from the product. Rapid cooling rates are therefore achieved. In general terms, a 5 °C reduction in product temperature is achieved for every 1 % of water that is evaporated. There are, however, disadvantages. Since it is a batch process, it requires greater production flexibility. The capital cost is high and, if the pressure is reduced too fast, internal boiling can damage the product.

In vacuum cooling, pre-wetting is commonly applied to reduce overall weight loss. Pre-wetting is also useful in products that do not have a large surface area in proportion to their mass. When pre-wetting, a thin film of water is best applied since coarse droplets will evaporate preferentially causing localized dehydration.

The advantages and disadvantages of vacuum cooling are shown in Table 15.3. In a similar way to microwave cooking, vacuum cooling is selective, in that it is the moisture-containing product rather than the container, which is cooled.

Table 15.3 Advantages and disadvantages of vacuum cooling in comparison with mechanical refrigeration

Advantages	Disadvantages
Low labor costs	Relatively high capital investment
Rapid cooling rate	Not applicable to all products
Selective cooling	Relatively high weight losses
Close temperature control	Batch process

Table 15.4 Advantages and disadvantages of total loss refrigerants in comparison with mechanical refrigeration

Advantages	Disadvantages
Low capital investment	High operating cost
High refrigerating capacity	High refrigerating capacity
Low weight when out of use	High weight at start of use
No residual weight (dry ice)	Limited duration without filling
No noise	Poor temperature control
Advantageous storage atmosphere (N_2)	Reduced humidity
Bacteriostatic affect (CO_2)	Suffocation hazard
Low maintenance requirements	Limited availability
Foolproof once installed (dry ice)	

15.2.6 Ice

Chilling with crushed ice or an ice–water mixture is simple, effective and commonly used for fish cooling. Cooling is more attributable to the contact between the produce and the cold melt water percolating through it (i.e., hydrocooling) than with the ice itself. Ice has the advantage of being able to deliver a large amount of refrigeration in a short time as well as maintaining an essentially constant temperature close to 0 °C. The clearest disadvantage of crushed ice treatment is a considerable labor requirement. However, automatic filling systems have been developed to offset this. Ice is also often used during cutting and mixing of meat products to prevent heating of the product due to the mechanical movement of the mixing and cutting blades.

15.2.7 Cryogenic

Cryogenic cooling uses refrigerants, such as liquid nitrogen or solid carbon dioxide, directly. The method of cooling is essentially similar to water-based evaporative cooling in that the reduction in temperature is brought about by boiling off the refrigerant. The essential difference is the temperature required for boiling. As well as using the latent heat absorbed by the boiling liquid, sensible heat is absorbed by the resulting cold gas.

Due to very low operating temperatures and high surface heat transfer coefficients between product and medium, cooling rates in cryogenic systems are often substantially higher than for other refrigeration systems. Most cryogenic systems employ total loss refrigerants, i.e., the refrigerant is released to the atmosphere and not recovered. Due to environmental and economic factors, total loss refrigerants must be both readily available and harmless. This limits the choice to atmospheric air and its components, liquid nitrogen (LN), and liquid or solid carbon dioxide (CO_2).

The particular characteristics of total loss refrigerants that may be regarded as advantages or disadvantages are listed in Table 15.4. They are mainly used for small products such as burgers, ready meals, etc. The simplest method involves direct spraying of liquid nitrogen onto a food product while it is being conveyed through an insulated tunnel. Avoiding surface freezing of the product is the main problem when using cryogens for chilling. In freezing, direct spraying can cause product damage and a countercurrent system is often employed where the product is initially cooled by cold gas before final spraying or immersion in liquid nitrogen.

Cooling of solids and solid–liquid mixtures during cutting and mixing is increasingly common to prevent heating of products due to the mechanical movement of the mixing and cutting blades. LN and liquid, or solid, CO_2 are commonly employed for such processes. The refrigerants are introduced directly through valves or spray bars, thereby ensuring controlled distribution and cooling. The gases provide more even and quicker chilling than ice, which has been used traditionally.

15.3 New or Novel Refrigeration Systems

Mechanical refrigeration has a history of research stretching back over 100 years. During this time, many new and novel technologies have been introduced; some have succeeded, and many have failed. Many chilling, freezing, and thawing systems consist basically of insulated rooms in which cold air is circulated from a refrigeration plant. Such systems are used because they are cheap to construct and very versatile. However, there is a growing trend for the food industry to consider alternate, “novel” systems for specific chilling, freezing and thawing processes. This trend is accelerating now that environmental considerations are forcing the industry to make changes to the refrigerants they use.

15.3.1 Environmental Considerations

The dominant types of refrigerant used in the food industry in the last 50 years have belonged to a group of chemicals known as halogenated hydrocarbons. Members of this group, which includes CFCs (chlorofluorocarbons) and HCFCs (hydrochlorofluorocarbons), have excellent properties, such as low toxicity, compatibility with lubricants, high stability, good thermodynamic performance and relatively low cost, all of which make them excellent refrigerants for industrial, commercial and domestic use. However, their high chemical stability leads to environmental problems when they are released and rise into the stratosphere. Scientific evidence clearly shows that CFC emissions damage the ozone layer and contribute significantly to global warming. As a result, their manufacture and use were banned under the terms of the 1987 Montreal Protocol (http://ozone.unep.org/new_site/en/index.php). Production of two refrigerants (the CFCs R12 and R502) commonly used in the food industry and elsewhere ceased in the mid-1990s. Although HCFCs, including R22, which is still widely employed in chillers and freezers, are less damaging to the environment, their use too is currently being phased out. The schedules adopted by the USA and the EU to meet their obligations under the Montreal Protocol are summarized in Table 15.5.

Chemical companies continue to make large investments in terms of both time and money in developing new refrigerants, which have reduced or negligible environmental effects. Some of these alternative refrigerants will be “drop in” replacements that can be used in existing refrigeration plants without major modifications or “retrofittable,” where changes may be required to lubricants or compressor speed. Other “non-retrofittable” replacements will have similar thermodynamic properties, but will require new refrigeration systems. Other researchers are reexamining the role of non-halogenated hydrocarbons in food-refrigeration applications.

Table 15.5 Timetable for phase out of HCFCs agreed under the Montreal Protocol

USA (EPA 2012)		EU (Carbon Trust 2007)	
1 January 2004	35 % Reduction in consumption and production using the cap as a baseline. Other restrictions on production and importation apply	2000–2004	Use of HCFCs in new refrigeration systems banned
1 January 2010	75 % Reduction in consumption and production using the cap as a baseline. Other restrictions on production and importation apply	1 January 2010	Use of virgin HCFCs for maintenance banned
1 January 2015	90 % Reduction in consumption and production using the cap as a baseline. Other restrictions on production and importation apply	1 January 2015	Use of recycled/reclaimed HCFCs for maintenance banned
1 January 2020	99.5 % Reduction in consumption and production using the cap as a baseline. Other restrictions on production and importation apply		
1 January 2030	100 % Reduction in consumption and production using the cap as a baseline. No production or import of any HCFCs		

15.3.2 New Alternative Refrigerants

The first reaction of the refrigeration and chemical industries to environmental pressure was to look for interim refrigerants, most based on R22, with friendlier environmental properties that could be used until more satisfactory long-term alternatives could be developed. Interim replacements for R502, for example, were Isceon 69S and 69L, Suva HP80 and HP81 and Atochem FX10. Suva MP39 and MP66 were developed as interim replacements for R12.

Several long term alternative refrigerants are now available on the market. The HFC (hydrofluorocarbon) R134a, for example, was the popular choice to replace R12 in a wide range of commercial refrigeration applications, including those in the food industry, in air conditioners, and in domestic refrigerators. R134a does not contain chlorine and, therefore, has an ODP of zero. As is the case with R12, it has low toxicity levels and a low boiling point. It was not a true “drop in” replacement because it is not compatible with the normal mineral lubricating oils used in R12 systems; special ester oils had to be developed. A simple procedure was employed using the ester oil to flush out the mineral oil from the refrigeration system during maintenance. Once the proportion of mineral oil had been reduced to approximately 1 % of the ester oil, the R12 was removed and R134a introduced.

Several chemical companies now market blends of HFC refrigerants, with a zero ODP, for use in applications in which R502 was widely used. Table 15.6 lists some common examples, together with their global warming potentials (GWPs) relative to carbon dioxide; as may be seen, these are all relatively high.

15.3.3 Old Alternative Refrigerants

Many non-CFC alternatives including ammonia, propane, butane, carbon dioxide, water, and air have been used in the past in food refrigeration systems. All have a zero ODP and very low GWPs (≤ 5.5) compared with the HFCs listed in Table 15.6.

Table 15.6 Commonly used blends of HFC refrigerants

ASHRAE designation	Trade names	GWP ($CO_2 = 1.0$)
R404a	Suva HP62, Forane FX-70	3,922
R407c	Klea 66	1,774
R410a	Suva 9100, Genetron AZ-70, Puron	2,088

After Wikipedia (2012)

Ammonia (R717) is the common refrigerant employed in large-scale industrial food cooling and storage plants. It is a cheap, efficient refrigerant whose pungent odor aids leak detection well before toxic exposure or flammable concentrations are reached. The renewed interest in this refrigerant has led to the development of compact low charge systems, which significantly reduce the possible hazards in the event of leakage. However, its use is not recommended in hermetically sealed compressors due to the fact that it is highly corrosive towards copper. It is expected that ammonia will meet increasing use in large industrial food refrigeration systems.

Ammonia also has a role in more sensitive areas, such as supermarkets, where a leak, however small and safe, is considered unacceptable. It is being used in remote plants as a primary refrigerant to cool secondary refrigerants such as water, brine, or glycol. These secondary refrigerants can then be pumped round the stores to provide the cooling required in air conditioning units and chilled and frozen stores and display cabinets. A number of systems are already in operation in Europe.

Various hydrocarbons have been considered for use in domestic refrigerators and much research has been carried out on their efficiency and safety. These studies have shown that in the quantities required within domestic systems there is only a minimal risk of fire or explosion. As a result, isobutane (R600a) has been widely adopted for this purpose in Europe and elsewhere (e.g., China). In the USA, the EPA recently (December 2011) approved the use of ethane (R170), propane (R290), butane (R600), isobutane (R600a), and a blend of these hydrocarbons (R441a) for use in household and small commercial refrigerators. The risk associated with the larger quantities required in commercial or industrial food refrigeration plants is significantly higher. This makes their use in these applications less likely.

15.3.4 Air Cycle Refrigeration

The growing awareness of the potential for environmental damage caused by CFCs, and of the limitations of vapor compression systems, has focused attention on alternative refrigeration cycles for the new Millenium. The most exciting alternative refrigerant, and the one that is totally environmentally friendly, is air. This is inherently the safest and cheapest refrigerant. It is also harmless to the environment, to human beings and food, and it is free.

The use of air as a refrigerant is not new. In the nineteenth century, it was used extensively in cold-store applications and in ship-based chilling systems. However, the development of vapor compression cycles, based initially on ethyl ether, ammonia, or sulfur dioxide, but later superseded by CFCs, produced systems with much higher efficiencies. However, since that time, air-cycle systems have been used extensively in aircraft air conditioning and the development of rotary compressors and expanders has greatly improved their efficiency and reliability. Advances in turbine technology, together with the development of air bearings and ceramic components, offer further increases in efficiency. Combining this with newly available compact heat exchangers with greatly improved heat transfer characteristics makes competition with existing vapor compression, and

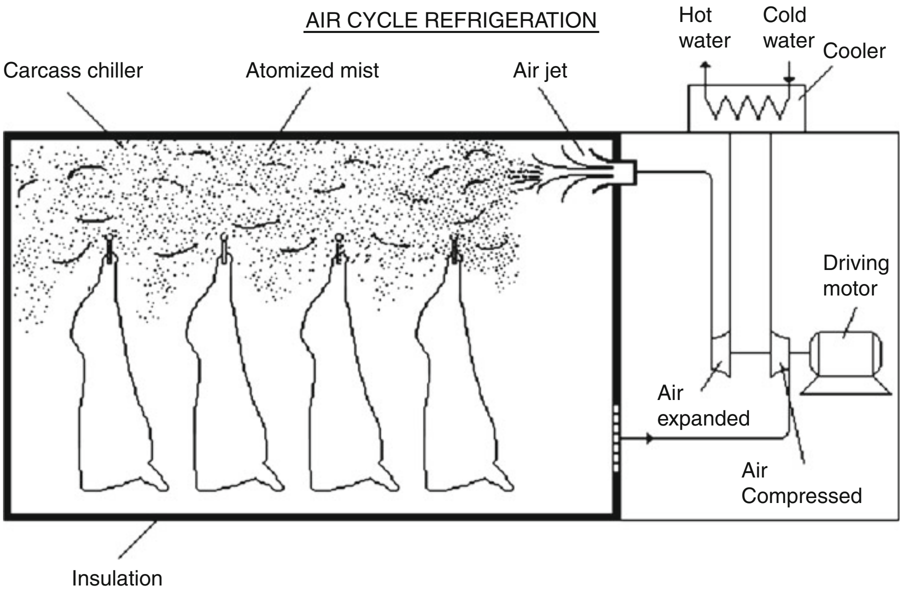


Fig. 15.4 Schematic of possible air-cycle chilling plant for meat carcasses

certainly liquid nitrogen systems, quite feasible. Air as the working fluid in refrigeration and heat pump systems shows great potential. Ongoing research work has already identified areas within the food industry where some of the air cycle's unique properties are advantageous. These properties include:

- The production of air at temperatures between −40 and −120 °C.
- The production of air at a controlled humidity.
- The recovery of heat at temperatures between 100 and 200 °C.

The use of air as a refrigerant is based on the principle that when a gas expands isentropically, its temperature is reduced. The resulting cold air can then be used as a refrigerant, either directly in an open system (Fig. 15.4), or indirectly by means of a heat exchanger in a closed system. In such systems, the efficiency is limited because heat transfer occurs over a range of temperatures and the efficiencies of compression and expansion have an important effect.

In food refrigeration there are specific benefits that can be gained from the air cycle's special performance characteristics. For many products, weight loss during air cooling is of significant concern. Air-cycle refrigeration can produce supersaturated air at chill temperatures, thus enabling chilling and chill storage to be carried out under conditions that minimize weight loss whilst maintaining product quality.

Recently, there has been a growing interest in the use of air cycles in many different processing fields. Air-cycle systems are being reintroduced for fast food freezing in the USA. In the former Soviet Union, air cycles have been used in food drying and freezing, storing biological samples and soil freezing, where there are simultaneous demands for process heating and cooling. The application of air-cycle refrigeration has much to offer the food industry. It is unlikely that it will be suitable for all food applications but its novel properties are unrivalled in many processes.

15.4 Specifying, Designing, and Optimizing Refrigeration Systems

15.4.1 Introduction

In specifying refrigeration equipment, the function of the equipment must be absolutely clear. Refrigeration equipment is always used to control temperature. Either the food passing through the process is to be maintained at its initial temperature, e.g., as in a refrigerated store or a packing operation, or the temperature of the food is to be reduced, e.g., as in a blast freezer. These two functions require very different equipment. If a room is to serve several functions then each function must be clearly identified. The optimum conditions needed for that function must be evaluated and a clear compromise between the conflicting uses made. The result will inevitably be a room that does not perform any function completely effectively.

There are three stages involved in the specification of a refrigeration plant. The first is determining the process specification. The second is drawing up the engineering specification, i.e., translating the food-processing conditions into terms that a refrigeration engineer can understand. The third and final stage is the procurement of the plant.

15.4.2 Process Specification

Poor design in existing chillers/freezers is often due to a mismatch between what the system was originally designed to do and how it is actually used. The first task in designing such plant is therefore the preparation of a clear unambiguous specification by the user of how the room will be used. Factors to be considered include throughput, temperature requirements, yield of product, future use, and plant layout.

15.4.2.1 Throughput

The throughput must be specified in terms of the product to be handled and its presentation, i.e., whether wrapped, unwrapped, cartoned, palletized, etc. When more than one product is to be processed, separate specifications must be drawn up for each. If, for example, the product is a raw material processed directly after slaughter or harvest, then the variability must be defined. With meat, the range and average of weight and fat content of each product should be specified. For example, large carcasses can take twice as long to chill as small carcasses under the same conditions. It is important to be realistic in deciding on the weight range. Simply to say that all types and weights of animals slaughtered are to go through the one chiller or freezer will inevitably mean that compromises must be made at the design stages, which will lead to a system that is quite inadequate.

A throughput profile is needed. Few food plants process the same quantity and type of product each day of the week. Simply to specify an average throughput is not adequate. The maximum capacity must be catered for and the refrigeration system should also be designed to operate economically at all other throughputs.

In the case of freezers, the throughput that can be handled by a given unit will certainly be influenced, if not determined, by the freezing rate. This, in turn, is purported to affect the quality of the frozen product, particularly in the case of foodstuffs having a low dry matter content and loose tissue (e.g., raspberries, tomatoes, and cucumbers). In practice, however, provided that the freezing rate is “reasonably fast,” considerations of cost will in most cases dominate over those of quality, particularly as conditions in the cold store may well determine the ultimate quality of the product delivered to the consumer. It is, however, important that the freezing process be completed in the freezer unit itself rather than in the cold store, where the freezing rate will be much slower.

15.4.2.2 Temperature Requirements

The temperature range required for each product must also be clearly stated. In deciding this, several factors, often conflicting, must be considered. These include legislation, current and future customer requirements, and internal standards. Finally, one must decide to what extent the above standards are mandatory.

15.4.2.3 Yield Loss

Many refrigeration processes affect the yield of saleable material. This can be either directly by reducing weight loss, or indirectly. An example of the latter occurs in bacon tempering in which appropriate specification of the conditions maximizes the quantity of high-quality slices produced. If yield is important, it is desirable to quantify at an early stage how much extra can be spent in order to save a given weight of product.

15.4.2.4 Future Use

All the information collected so far, and the decisions taken, will relate to existing or immediately envisaged production. Another question that needs to be asked is, will there be any changes in the use of the refrigeration system in the future? The life of a typical chiller/freezer is anything between 10 and 50 years (judging by the present chiller/freezer population) and many food plants will expand over such a period. What changes can be envisaged? These should be quantified in as much detail as possible.

15.4.2.5 Plant Layout

Chilling, freezing, etc., is one operation in a sequence of operations. It influences the whole system and interacts with it. An idea must be obtained as to how the system is to be loaded, unloaded, and cleaned. These operations will always be intimately involved with those of the process line, the sales team, and the loading bay. Questions that need to be addressed are: where will product be sorted into individual orders and where will unsold product be stored until a future date? There is often a conflict of interest within a chiller/freezer. In practice, the system is often used as a marshalling yard for sorting orders and as a place for storing food, which has not been sold. If it is envisaged that either of these operations will take place in the system, the design must be made much more flexible. It must also cover the conditions needed in a marshalling area or a refrigerated store.

Food must be loaded into and removed from the freezer or chiller. These operations may be continuous, batch or semi-continuous. In the case of batch and semi-continuous processing, holding areas will be required at the entrance and exit of the freezer/chiller in order to even out material flows from or to adjacent processing units. The available time for chilling or freezing will, in part, be dictated by the available holding area. For a given throughput, a slow process will require a greater area than a fast process. It may also be dictated by commercial constraints, such as the delivery of product to distribution outlets.

The above specifications will dictate the processing conditions. In most cases, air is used as the cooling medium and its temperature, velocity, and relative humidity are usually all critical to the success of the operation. If a single-stage process is employed, steady values will be specified. In the case of multistage processes, however, these variables may be time dependent. Choosing the operating conditions will involve an interaction with the earlier specified constraints. Some compromise may be needed, for example, adjusting the processing time available, in order to obtain an optimal solution. Once the process conditions are fixed and the throughput and materials specified, the product load will also be fixed although this may not always be known. Where design data exist, they should be utilized to specify the product load.

Other refrigeration loads also need to be specified. Many of these, such as infiltration through openings, the use of lights, machinery and people working in the refrigerated space, are under the control of the user. They must be specified so that the heat load given off by them can be incorporated into the final design. Ideally, all the loads should be summed together on a time basis to produce a load profile. This is most important if the refrigeration process is to be linked to other process operations within a plant, as it affects the operating costs.

The ambient design conditions must also be specified as must the defrost regime. There are times in any process when it is critical to avoid a defrost. Therefore it is important that the coil be cleared of frost before commencing this part of the operation.

The above requirements should all be specified by the end user. It is common practice throughout European industry to leave much of this specification to refrigeration contractors or engineering specialists. However, since all the above are outside their control, the final decision should always be taken by the end user, based upon a knowledge of how well the overall process can be controlled.

15.4.3 Engineering Specification

15.4.3.1 Aim and Scope

The aim of drawing up an engineering specification is to turn the processing conditions into a specification that any refrigeration engineer can then use without knowledge of the food involved. If the first part of the process specification has been completed then the engineering specification will be largely in place. It specifies the environmental conditions within the refrigerated enclosure, i.e., air temperature, velocity, and humidity. It will define the way the air will move within the refrigerated enclosure; the size of the equipment; the refrigeration load profile; the ambient design conditions; and the defrost requirements.

The final phase of the engineering specification should be to draw up a schedule for testing the engineering specification prior to handing over the equipment. This test will be in engineering and not product terms.

15.4.3.2 Estimation of Chilling and Freezing Times

A critical step in drawing up the engineering specification is the estimation of the time required to chill or freeze the required product under the specified environmental conditions. In both cases, an accurate knowledge of the thermal and other physical properties of the food is required. In many cases, such properties will not be known with great precision because of the inherent variability of biological products. Chilling times can be estimated using standard unsteady-state heat transfer techniques, which are widely documented (see for example Cleland 1990; Toledo 1991).

Increasingly, programs such as BeefChill and FoodTemp based on finite difference techniques are being used to predict chilling times, surface changes, and rates of heat loss.

Freezing times are more difficult to calculate for a variety of reasons. The classical method involves the use of Plank's equation, which, for a one-dimensional infinite slab may be written

$$t_\mathrm{f} = \frac{\rho\lambda}{(T_\mathrm{if} - T_\mathrm{a})}\left[\frac{R}{h} + \frac{R^2}{2\kappa_\mathrm{f}}\right], \tag{15.1}$$

where t_f is the freezing time, ρ is the density of the product (assumed to be the same in the unfrozen and frozen states), λ is the latent heat of fusion, T_if is the initial freezing temperature of the product, T_a is refrigerated air temperature, R is half-thickness of the slab, h is the convective heat transfer coefficient (calculated from standard correlations, see for example Cleland and Valentas (1997)), and κ_f is the thermal conductivity of the frozen product. Variants of this equation have been derived for spheres, infinite cylinders and finite parallelepiped geometries but the analytical approach employed is unlikely to applicable to the complex product shapes encountered in practice. Cleland and Valentas (1997) recommend the use of a more accurate empirical equation based on Plank's equation:

$$t_\mathrm{f} = \frac{1}{E}\left(\frac{\Delta H_1}{\Delta T_1} + \frac{\Delta H_2}{\Delta T_2}\right)\left[\frac{R}{h} + \frac{R^2}{2\kappa_\mathrm{f}}\right]. \tag{15.2}$$

Here

$$\Delta H_1 = \rho c_\mathrm{u}(T_\mathrm{i} - T_\mathrm{mf}).$$

$$\Delta H_2 = \rho\lambda + \rho c_\mathrm{f}(T_\mathrm{mf} - T_\mathrm{fin}).$$

$$\Delta T_1 = 0.5(T_\mathrm{i} - T_\mathrm{mf}) - T_\mathrm{a}.$$

$$\Delta T_2 = T_\mathrm{mf} - T_\mathrm{a}.$$

$$T_\mathrm{mf} = 1.8 + 0.263T_\mathrm{fin} + 0.105T_\mathrm{a}.$$

and c_u and c_f are the heat capacities of the unfrozen and frozen product, respectively, T_i is the initial temperature of the product, and T_fin is the final temperature at the thermal center of the product, which is the slowest point to cool. In this case, the characteristic half-thickness R is defined as the shortest distance between the thermal center and the product surface.

The effect of shape on freezing rate is accounted for by the factor E. The value of this parameter lies between 1 and 3; it is a measure of how much each of the spatial dimensions contributes to heat transfer. For an infinite slab, $E = 1$, for an infinite cylinder, $E = 2$, and for a sphere, $E = 3$. For other product shapes, E can be estimated from:

$$E = 1 + \frac{\left(1 + \frac{2}{Bi}\right)}{\left(\beta_1^2 + \frac{2\beta_1}{Bi}\right)} + \frac{\left(1 + \frac{2}{Bi}\right)}{\left(\beta_2^2 + \frac{2\beta_2}{Bi}\right)}, \tag{15.3}$$

Where

$$\beta_1 = \frac{A}{\pi R^2}, \tag{15.4}$$

$$\beta_2 = \frac{3V}{4\pi\beta_1 R^3}, \tag{15.5}$$

$$Bi = \frac{hR}{\kappa_\mathrm{f}}, \tag{15.6}$$

and V is the volume of the product and A its smallest cross-sectional area measured through the thermal center. Some typical measured values of E quoted by Cleland and Valentas (1997) are as follows: Lamb (shoulder) 1.4, Lamb (deep leg) 2.0, Beef side (deep leg) 1.3, Albacore tuna fish 1.8.

Accurate predictions of chilling and freezing times require an equally accurate knowledge of the thermal properties of foods. In practice these are somewhat variable. Jowitt et al. (1983) provides a useful source of data based on the European COST-90 program. Computer programs such as COSTTHERM and FoodProp are now widely available to predict the thermal properties of a food from its chemical composition. Integrated programs, e.g., FoodTemp will initially calculate the thermal properties and then use these properties in their in their prediction of either a chilling or a freezing time.

15.4.3.3 Importance of the Engineering Specification

The user must play an active part in the development of the engineering specification because a number of the decisions taken in this stage will affect other aspects of his operation. The specification produced should be the document that forms the basis for quotations. It will also form the basis of the contract between the user and his contractor. It must therefore be stated in terms that are objectively measurable once the system is completed. Arguments often ensue between contractors and their clients as a result of an unclear, ambiguous or unenforceable specification. Such lack of clarity is often expensive to all parties and should be avoided.

15.4.4 Procurement

The engineering specification should be sent out to tender. If potential suppliers have been selected for the quality of their equipment and all accept the tender conditions and agree that they can meet the specified design and test requirements, the lowest tender would normally be chosen. The contractor is normally responsible for the detailed engineering design, construction and commissioning. The client will only need to check that this work is carried out in a professional manner. His first major responsibility is to carry out the acceptance tests to confirm that the performance of the refrigeration equipment meets the engineering specification. The plant should not be accepted until these tests have been carried out satisfactorily. It can then be handed over and the plant operators given the necessary training in its correct use. The plant should then be commissioned by the factory personnel, who will systematically increase the throughput until the desired value is achieved. Finally, the original process specifications should be tested to ensure that the intended results are in fact achieved in terms of temperatures, throughputs, and yield.

15.4.5 Summary Points

The performance of refrigeration systems is a major source of conflict between users and plant contractors. Adopting the approach outlined in this chapter should avoid these conflicts. If performance problems occur, then the approach will clearly identify which partner is responsible for sorting them out.

1. The user must accept responsibility for the process specification. This should clearly identify what he wishes to achieve and should take into account any expansion plans. Outside input may be used to help the user clarify his requirements and options but the final decision is his.
2. From a clearly defined process specification, an engineering specification can be written. This will define the requirements in terms of the conditions that have to be met within the refrigerated enclosure. It will also define the space limitations, etc., the tests to be carried out before acceptance, and any monitoring/control instrumentation to be supplied.
3. The process specification and its development into an engineering specification are critical steps in obtaining a refrigeration system that works satisfactorily. The rest of the procedure should follow automatically. However, the cost factor should not be forgotten. Frequently, the initial quotations are outside the user's budget and during discussions cost savings are agreed. All too often there is an implied change to the engineering specifications and consequently to the process specification. Unless this is formally recognized and the specifications amended to take into account the change, a future source of conflict will have been established.
4. Once the plant has been constructed and commissioned, routine monitoring and action when performance changes are the final key tasks in the maintenance of an optimum refrigeration system.

References

Carbon Trust (2007) "R22 phase out and F-gas regulations", Food & drink industry refrigeration efficiency initiative, Guide 4, Carbon Trust, July, 19 pp. Available online at http://www.comserve.co.uk/uploads/files/e68636_carbon%20trust%20r22-fgas%20feb09.pdf.

Cleland, A.C. (1990) "Food refrigeration processes – Analysis, design and simulation", Elsevier Applied Science Publishers, London, 284 pp.

Cleland, D.J. and Valentas, K.J. (1997) "Prediction of freezing time and design of food freezers", in "Handbook of Food Engineering Practice", (eds) Valentas, K.J., Rotstein, E. and Singh, P.R., CRC Press, New York, 718 pp.

EEC (1976) "Laying down common standards for the water content of frozen and deep-frozen chickens, hens and cocks", Council Regulation (EEC) No. 2967/76, 23 November 1976. Available online at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31976R2967:en:NOT.

EEC (1980) "Introducing detailed rules for implementing Regulation (EEC) No 2967/76 laying down the common standards for the water control of frozen and deep-frozen chickens, hens and cocks", Commission Regulation (EEC) No 2785/80, 30 October 1980. Available online at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31980R2785:en:NOT.

EPA (2012 "Ozone layer protection – Regulatory programs", US Environmental Protection Agency, updated 2 February, www.epa.gov/ozone/title6/phaseout/hcfc.html.

Jowitt, R., Escher, F., Hallstrom, B., Meffert, H.F.T., Speiss W.E.L., and Vos, G. (1983), (eds) Physical properties of foods", Applied Science Publishers, London.

Toledo, R. (1991) "Fundamentals of food process engineering', 2nd edit., Van Nostrand Reinhold, New York.

Wikipedia (2012) "List of refrigerants", modified 14 April, www.en.wikipedia.org/wiki/List_of_refrigerants.

Further Reading

Anonymous (1974) “ASHRAE handbook and product directory. Applications”, American Society of Heating Refrigeration and Air Conditioning Engineers, New York.

FRPERC (1997) “Meat refrigeration – Why and how?”, EU Concerted Action Programme CT94 1881, Food Refrigeration and Process Engineering Research Centre, Langford. FRPERC is now located at the Grimsby Institute (www.grimsby.ac.uk/industry/FRPERC.php).

FRPERC (2000) “Publications on the refrigeration and thermal processing of food”, University of Bristol, FRPERC is now located at the Grimsby Institute (www.grimsby.ac.uk/industry/FRPERC.php).

Gormley, T.R. (1990) “Chilled foods – The state of the art”, Elsevier Applied Science, Barking, 385 pp.

International Institute of Refrigeration (1979) “Recommendations for chilled storage of perishable produce”, International Institute of Refrigeration, Paris.

International Institute of Refrigeration (1985) “Technology advances in refrigerated storage and transport”, International Institute of Refrigeration – Commissions D1, D2 & D3, Orlando.

International Institute of Refrigeration (1986) “Recommendations for the processing and handling of frozen foods”, International Institute of Refrigeration, Paris.

International Institute of Refrigeration (1986) “Recent advances and developments in the refrigeration of meat by chilling”, International Institute of Refrigeration – Commission C2, Bristol.

International Institute of Refrigeration. (1990) “Progress in the science and technology of refrigeration in food engineering”, International Institute of Refrigeration – Commissions B2, C2, D1, D2/3, Dresden.

James, S.J. (1999) “Food refrigeration and thermal processing at Langford, UK: 32 years of research”, Trans. IChemE, Food and Bioproducts Proc., Vol. 77, Part C, December, pp. 261–279.

Zeuthen, P., Cheftel, J.C., Eriksson, C., Gormley, T.R., Lonko, P. and Paulus, K. (1990) “Chilled foods: The revolution in freshness”, Elsevier Applied Science, Barking.

Chapter 16
Heating, Ventilation, and Air Conditioning

G.L. Quarini

16.1 Introduction

The heating, ventilation, and air conditioning problems encountered by the food manufacturing industry are similar but different to those faced by parts of the pharmaceutical, general medical, defense, and electronics industries. Essentially they are ones of ensuring that the employees benefit from a safe, comfortable, and productive environment, whilst the activities are undertaken in hygienic and temperature/humidity controlled conditions, which facilitate the manufacture of consistently good products. The special facet associated with the storage, processing and manufacture of food is that specific foods need well-defined conditions, e.g., very cold environments for storing frozen meats, a cool hygienic environment for fresh chilled foods.

In most developed countries, local or national building regulations will specify minimum acceptable insulation for buildings. Recent concerns over climate change have resulted in many countries introducing taxation which penalizes the inefficient use of energy. This has led to food manufacturers becoming particularly aware of the energy implications of not optimizing their heating and ventilation requirements.

Thus, the three major drivers for improved heating, ventilation, and air conditioning are as follows:

1. Food safety and quality: the engineered environment must facilitate the production of safe, high quality products with long shelf-lives.
2. Comfortable working environment: the environment should, as far as possible, be pleasant and productive. This includes thermal comfort for the employees in offices and on the shop floor.
3. Energy considerations: this aspect has become more important in recent times, partly as a result of increasing energy costs, but also, and perhaps more dramatically, the perceived detrimental impact of the profligate use of energy.

Taking each in turn will help identify the requirements for heating, ventilation, and air conditioning and the engineering solutions to these needs.

G.L. Quarini (✉)
Department of Mechanical Engineering, University of Bristol, Bristol BS8 1TR, UK
e-mail: joe.quarini@bristol.ac.uk

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_16,

16.2 Optimized Environments

16.2.1 Food Production

It is imperative that the appropriate environmental conditions are maintained in the manufacture of certain chilled fresh foods, where very cold temperatures (below the freezing point) cannot be used to stop or severely reduce microbial activity, and where even relatively minor excursions in temperature will lead to reduced shelf life, spoilage or in some cases unsafe food. The ventilation strategy should be such as to minimize any air-borne contamination from factory workers to these chilled foods. The situation is less demanding in the cases of some ambient stable foods, where microbial activity tends not to be a problem. However, even in these cases it is important that appropriate ventilation and air conditioning strategies be adopted so as to ensure that high levels of hygiene are naturally maintained. In some cases, the production or storage of foods results in quite arduous production environments, the effects of which can be at least partially alleviated by adequate ventilation. Examples include hot industrial bakeries, where ventilation helps to keep the work space a little cooler, and frozen stores, where air curtains help to minimize heat gains, without increasing the chill factor throughout the store.

16.2.2 Thermal Comfort for Employees

Perceived thermal comfort appears to be dependent on two major factors; the first is that the human body needs to be at about 37 °C. The second is that the heat loss from the body is equal to the metabolic gain so that there is no net temperature rise or fall. Before these requirements are converted to design factors, it is necessary to understand how the body controls its temperature. As a result of metabolic processes, heat is generated within the body, and all of this heat must be transferred from the body to its surroundings. For a typical worker undertaking "light" duties on a production line or in an office environment, 40 % of the heat loss is through convection, 40 % through radiative heat transfer and 20 % through evaporation. This evaporation is moisture loss from the lungs and evaporation (not sweating) through the skin. Sweating occurs if the skin temperature reaches 34 °C or more, or the metabolic rate is raised to high levels. Evaporative cooling becomes increasingly less efficient as the ambient relative humidity increases.

Although each person is different, individual comfort is related to the ease with which the individual manages to lose heat at his current metabolic rate, so as to maintain the desired 37 °C temperature. This is affected by the metabolic rate itself and the insulation (clothing) used by the employee as well as the environment in which he finds himself. There are four environmental features worthy of consideration in this respect: air temperature, air velocity around the employee, mean radiant temperature, and relative humidity.

16.2.3 Energy Considerations

This has become particularly important recently because of the perceived correlation between climate change and the world's carbon dioxide emissions, which tend to be synonymous with energy production and use. This has resulted in many governments setting energy conservation targets for most industries, including the food manufacturing industries. Refrigeration cooling and air conditioning accounts for 10–20 % of electricity consumption in most developed countries; for the UK in 2005, this figure was 17 %. Supermarkets (chilled display cabinets), cold stores (for meat as well as fruit and vegetables) and chilled food manufacturers are some of the heaviest energy consumers in this area. Baking ovens, tinned food manufacturers, and dairies are also heavy users of energy. All are being encouraged by financial incentives to reduce their energy consumption per unit produced. All recognize that heating, ventilation, and humidity control can help.

Thus, the design of heating, ventilation, and air conditioning systems in food factories is being driven by the needs to guarantee food safety, to increase and enhance food product quality and shelf life, to engineer a comfortable working environment, and to minimize energy use. In the following section, the basic underlying principles of heating and ventilation are briefly presented; this is followed by a focused section on the design policies and features adopted for food factories. Finally, some of the simple as well as the more advanced design tools employed are described.

16.3 Underlying Heating, Ventilation, and Air Conditioning Philosophies

16.3.1 Background: Need for Ventilation and Typical Ventilation Rates

Within a working environment there is a minimum amount of fresh air that will be required to enable the operators to breath; this is quite small (typically about 0.2 l/s per person). To achieve comfortable and safe working conditions, the air supply has to be much higher; the exact value depends on a number of factors and has to be large enough to deal with the following:

1. The dilution of odors to acceptable levels.
2. The dilution of toxic or irritant gases/vapors (including perhaps carbon dioxide) to acceptable levels.
3. Maintaining temperatures within desirable limits.
4. Holding humidity within acceptable levels and managing or eliminating condensation problems.

Over the past 50 or so years, recommendations and regulations have appeared which help architects and building services engineers establish sensible ventilation strategies for different conditions. The original work that led to the first recommendations was based on monitoring the amount of outside air that was needed to satisfactorily reduce odors or smells indoors. The actual amount depended on the number of people, their personal hygiene, what they did, from quiet and sedentary to active or even smoking, and the volume of the space they occupied. Experimental findings indicated that the amount of air per individual required to produce acceptable odor control decreased with increasing room volume available per person. Typical recommended values of air supply rate vary from 10 l/s per person for office workers, with a no smoking policy in place and no significant pollutant sources, to 40 l/s per person in smoking rooms. However, as mentioned at the beginning of this chapter, energy conservation measures are tending to encourage the use of lower ventilation rates, as this reduces energy demands for pumping the air and for conditioning it (either heating or cooling).

There are three methods of expressing ventilation rate: air changes per hour, liters per second per person and liters per second per meter square. The use of liters per second per person is appropriate where the number of people or operatives is well characterized. When the occupancy is unknown or varies, it is more appropriate to use liters per meter square. Note that the area of a typical office is about 9 m^2 per person and that a common value of ventilation rate based on floor area is 1.4 $l/s/m^2$.

The values quoted above can only refer to some mean ventilation rates that have been found to give reasonable levels of acceptability in pseudo steady state (time averaged) operations. In order to optimize ventilation regimes so as to provide fresh air when it is needed, it is necessary to describe the concentration of pollutants as a function of time. Further, introducing fresh air, whose condition may be different from that of the air already in the room, may result in changes to the air temperature and humidity. The sections below derive the transient equations for temperature, humidity, and species concentration. The derivations make the assumption that the air within the room is perfectly mixed.

16.3.2 Desired Conditions and Methods of Prediction

People want to feel comfortable. This implies the following conditions: temperature between 16 and 27 °C, humidity between 45 and 60 %, carbon dioxide levels less than about 0.1 %, and no noticeable unpleasant odors. Food materials and food manufacturing processes, on the other hand, may require very different conditions.

There are a significant number of publications describing the dependence of human comfort on the condition of the immediate surroundings. This suggests that for one to feel comfortable, the metabolic rate, M, of energy production should be matched to the work output, W, plus heat losses, H, so as to maintain the body temperature at around 37 °C. In other words:

$$M - W = H = E + R + C + S,$$

where the heat losses H have been divided into evaporative, E, radiative, R, and convective, C, components. Although S is not strictly a loss term, it has been included as it represents the transient storage of heat in the body when the body temperature is increasing or decreasing. Typical metabolic rates for an adult with a surface area of 1.8 m^2 (typical of a 1.8 m tall, 70 kg male) vary from 70 W while sleeping, to 400 W while walking at 4 mph, to 2,000 W whilst engaged in athletic bursts of power. The area is complex, and can be somewhat subjective, with some individuals feeling quite comfortable, others feeling cold and some feeling hot, even though they are all in the same room. Most countries have building regulations and legislation, which recommend/impose desirable temperatures, humidities, and ventilation rates in working environments. These will differ depending on the environment and on the activities.

Most fresh foods have a longer shelf life if kept at well below room temperature. The exceptions to this are some fruits (bananas and tomatoes, which store well at 12–15 °C) and some vegetables (new potatoes, stored at 12 °C). Most other fruits, vegetables, and fresh meats are best stored at a temperature just above that at which freezing might occur within the foodstuff, typically -1 to 4 °C.

This makes the design of a heating, ventilation, and air conditioning system for a typical food factory a challenge; it is difficult enough engineering comfort for all people-related activities; these difficulties are exacerbated when the needs of the food products have to be accommodated. For example, in the UK, regulations require that foods that are likely to support the growth of pathogenic microorganisms or the formation of toxins be held at or below 8 °C (or above 63 °C). However, health and safety requirements state that a “reasonable” temperature of at least 16 °C (or at least 13 °C if the work involves serious physical effort) be maintained throughout the workroom. This then implies providing means of chilling food locally or minimizing its exposure to ambient air, in situations where food needs to be maintained at below ambient temperatures. Meeting the twin objectives of controlling food product temperatures as required by hygiene legislation and working air temperatures as required by health and safety legislation may require food producers/processors to develop new processing methods, equipment and techniques. However, adopting localized chilling of food products and minimizing processing times can bring cost benefits compared with the overall installation and running costs of refrigerating whole workrooms or factories.

Innovative solutions to localized chilling requirements are more easily adopted and adapted into the design of new food processing plants. For existing plants, consideration should be given to the provision of, for example, heated rest facilities, suitable protective clothing, and local heating for the workers to improve personnel comfort.

In the following sections, two methods are presented, which can be adopted to study the distributions of temperature and humidity in both time and space. The first is a simple but powerful analytical technique that assumes that everywhere in the workroom the air is so well mixed that its properties are uniform and independent of spatial position. However, the air temperature and humidity and pollutant concentration do vary with time. This technique is an ideal tool to obtain quick estimates of what ventilation is required to achieve prescribed conditions, and how changes will affect the working environment. The second is more complicated but has the considerable advantage of being able to handle complex spatial variations. This second method adopts Computational Fluid Dynamics, CFD, techniques to model air flows within a computational domain. As well as predicting the flow distribution, it is also capable of computing the distributions of temperature, humidity, and pollutant concentration.

16.4 Simple Analytical Methods

16.4.1 Derivation of Transient Equations for Temperature, Humidity, and Pollutant Concentration

The controlling equations for temperature, humidity, and pollutant concentrations are all similar. However the mathematics and physical mechanisms controlling these quantities are very different. Some of the differentiating features between the processes controlling the transient behavior of temperature, humidity, and pollutant distributions include the following:

1. Heat transfer can occur through solid walls, while the walls are usually assumed to be impermeable to moisture and other pollutants.
2. Water vapor is assumed to "disappear" if conditions (temperature) are such as to allow condensation to occur. In practice, condensation will occur on the coldest parts when the relative humidity reaches 100 %.
3. Specific pollutants are also assumed to disappear if they decay or transmute. These processes may indeed be sources of other pollutants.

It is clear that these processes can be coupled; a drop in temperature can lead to the removal of water vapor by condensation. The condensation process will provide heat inputs (W) to the temperature equation via latent heat release. Condensation can "wash-out" pollutants and effectively act as an enhanced pollutant sink. The full mathematical derivation of these transient equations is given in Appendix 1. Here, we will focus on the physics of just one, the equation describing the variation of pollutant concentration with time, and deduce its form from first principles.

Consider a room of volume V m^3 that contains air with a pollutant concentration C g/m^3 (Fig. 16.1). Assume that there is a flow of air entering and leaving the room of Q m^3/s. The air

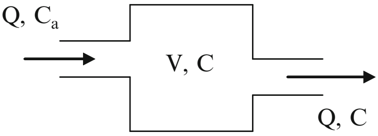
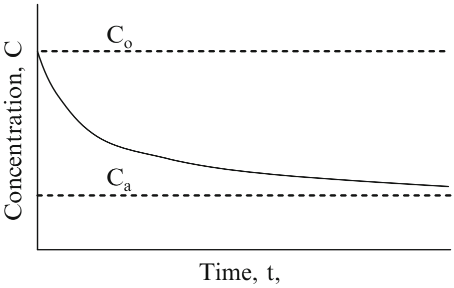


Fig. 16.1 Simple representation of a passive room of volume V being ventilated at a rate Q

Fig. 16.2 Typical variation of pollutant concentration C with time t during ventilation



flow entering the room has a pollutant concentration C_a g/m^3, whilst that leaving the room has a pollutant concentration C g/m^3.

It follows from a material balance that the rate of change of the mass of pollutant within the room must equal the net difference between the masses of pollutant entering and leaving the room. That is:

$$V\frac{\mathrm{d}C}{\mathrm{d}t} = QC_a - QC. \tag{16.1}$$

This is a simple first-order differential equation, which has the solution:

$$C = C_0 \exp\left(-\frac{Q}{V}t\right) + C_a\left[1 - \exp\left(-\frac{Q}{V}t\right)\right], \tag{16.2}$$

where C_0 is the initial value of C in the room at time $t = 0$. This equation can be written in terms of number of air changes per unit time, n (= Q/V):

$$C = C_0 \exp(-nt) + C_a[1 - \exp(-nt)]. \tag{16.3}$$

Figure 16.2 shows a typical C versus t curve, with the concentration within the room decreasing exponentially from the initial C_0 value to C_a, the value of C for the fresh incoming air.

In Appendix 1, it is shown that this analysis can be extended to include more complex systems in which there are pollutant sources in the room, E g/s, and in which the pollutant itself decays away at a given rate, k (1/s). This more complex situation has the solution:

$$\begin{aligned} C &= \left(\frac{QC_a + E}{Q + kV}\right)\left\{1 - \exp\left(-\left(\frac{Q}{V} + k\right)t\right)\right\} + C_o \exp\left(-\left(\frac{Q}{V} + k\right)t\right) \\ &= \left(\frac{nC_a + E/V}{n + k}\right)\{1 - \exp(-(n + k)t)\} + C_o \exp(-(n + k)t). \end{aligned} \tag{16.4}$$

16.4.2 Prediction of Condensation

A major problem that has to be faced in factories in which there is a need to handle food requiring chilling is condensation. This occurs when the relative humidity in the air reaches 100 %. This is a common occurrence, especially if there are warm zones with humidity-generating operations and activities as well as cool areas and cold surfaces. The problem can be tackled by reducing water vapor sources, by insulating cold surfaces, by warming the room air or by increasing the ventilation rate. The equations provided in Appendix 1 can be used to predict the humidity and the temperature of the air. Appendix 2 provides a method of estimating whether condensation is likely to be a problem and, if so, the ventilation rates required to alleviate the problem. Worked examples are provided in Sect. 16.6.

16.5 Computational Fluid Dynamics

16.5.1 CFD Background

The past 30 or so years has witnessed dramatic advances in the general area of Computational Fluid Dynamics (CFD), from its customized and idiosyncratic use by enthusiasts in the aerospace, defense, and nuclear industries, running codes on what were then super computers, to the more recent use of commercial CFD software packages for problem solving by engineers in the process industries. There are now a number of reputable software houses that offer commercial, general-purpose CFD packages that can be run on PCs. These packages can be relatively easy to use, but do require some investment in time on the part of the user. All commercial CFD codes purport to solve the continuity and momentum (the Navier–Stokes) equations for fluid flow. Once these equations are solved, it is relatively easy to solve for the transport of passive scalars such as humidity and inert pollutants. Most commercial software vendors also provide graphics packages to help display the CFD results. These can provide quite impressive visualizations of the predicted results.

It should be noted that at present it is still not possible to solve the full Navier–Stokes equations for a full-scale factory environment where the turbulence is high, and the topology and physics are very complex. The major problem arises from our inability (with current or immediately foreseeable computing power) to represent the complexity of turbulent flows accurately. It is therefore common practice to "smear out" the small-scale turbulent motions in order to produce a set of equations for the mean field only using one of a number of well-documented turbulence models. Probably the most widely used one is the "k-ε model", where k denotes the turbulent kinetic energy and ε the turbulent dissipation. The full equations are beyond the scope of this chapter. Those interested in this topic are referred to one of the commercial vendors of these codes and/or the following references cited at the end of this chapter: Anderson et al. (1984), ASHRAE (1999), CIBSE (2001), Ferziger and Peric (1997), GOV.UK (2013), HSE (2011, 2013), HMSO (2004), Jensen and Friis (2004), Jones (2001), Peyret (1996), Trott and Welsh (2000), and Wilcox (1993). However, it is instructive for those wishing to get a feel for the complexity of the underlying physics, to appreciate that even the "simplified" forms of the continuity, momentum, and scalar equations are really quite demanding. The following equations give a flavor of the complexity of the problem:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho U_{\mathrm{i}})}{\partial x_{\mathrm{i}}} = 0. \tag{16.5}$$

$$\frac{\partial (\rho U_{\mathrm{i}})}{\partial t} + \frac{\partial \left(\rho U_{\mathrm{i}} U_{\mathrm{j}}\right)}{\partial x_{\mathrm{j}}} = -\frac{\partial p}{\partial x_{\mathrm{i}}} + \frac{\partial}{\partial x_{\mathrm{j}}}\left(\mu \frac{\partial U_{\mathrm{i}}}{\partial x_{\mathrm{j}}} - \overline{\left(\rho u_{\mathrm{i}} u_{\mathrm{j}}\right)}\right) + S_{\mathrm{u}}, \tag{16.6}$$

where U_{i} and U_{j} are time-averaged velocities u_{i} and u_{j} are fluctuating quantities, and ϕ is any scalar quantity, for example temperature.

$$\frac{\partial (\rho \phi)}{\partial t} + \frac{\partial \left(\rho \phi U_{\mathrm{j}}\right)}{\partial x_{\mathrm{j}}} = \frac{\partial}{\partial x_{\mathrm{j}}}\left(\Gamma \frac{\partial \phi}{\partial x_{\mathrm{j}}} - \overline{\left(\rho \phi u_{\mathrm{j}}\right)}\right) + S_{\phi}. \tag{16.7}$$

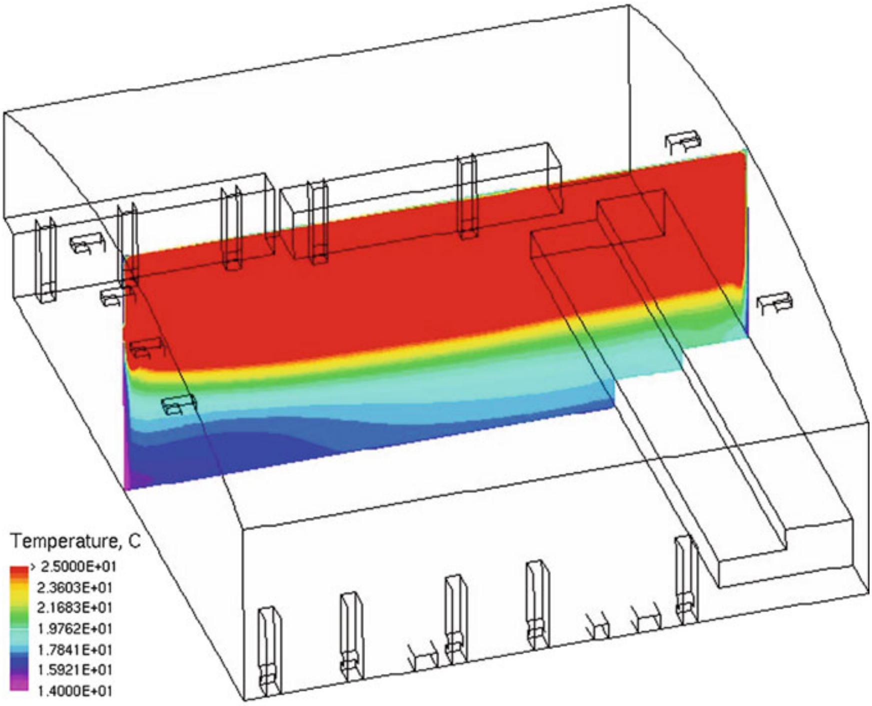


Fig. 16.3 Temperature distribution in a 120 m × 70 m × 30 m store room. Note the stratification, with cold air spilling in at the bottom and warm air in the upper zones

The turbulence models mentioned above provide closed expressions and equations for the complex nonlinear fluctuating quantities

$$\overline{(\rho u_\mathrm{i} u_\mathrm{j})} \text{ and } \overline{(\rho \phi u_\mathrm{j})}. \tag{16.8}$$

The purpose of providing these equations is not to frighten or put the reader off, it is to highlight two facts:

1. The underlying physics of CFD is far from trivial.
2. Because the physics is quite comprehensive, CFD is capable of modeling very demanding problems associated with ventilation within complex topologies.

16.5.2 *Some CFD Examples*

To make CFD technology useful to engineers and designers, it is important that the processes associated with solving the above equations are made available in an easy to use fashion. Typical commercial CFD packages offer the user a choice of turbulence models, then discretize the differential equations, solve the resultant algebraic matrices and provide graphics software to display the solutions. The user has to provide the topology, choose sensible physical models (for example, if buoyancy is important, how should it be represented?) and apply boundary conditions. Again, as an example of what can be done with CFD, Figs. 16.3 and 16.4 present some predictions for temperature

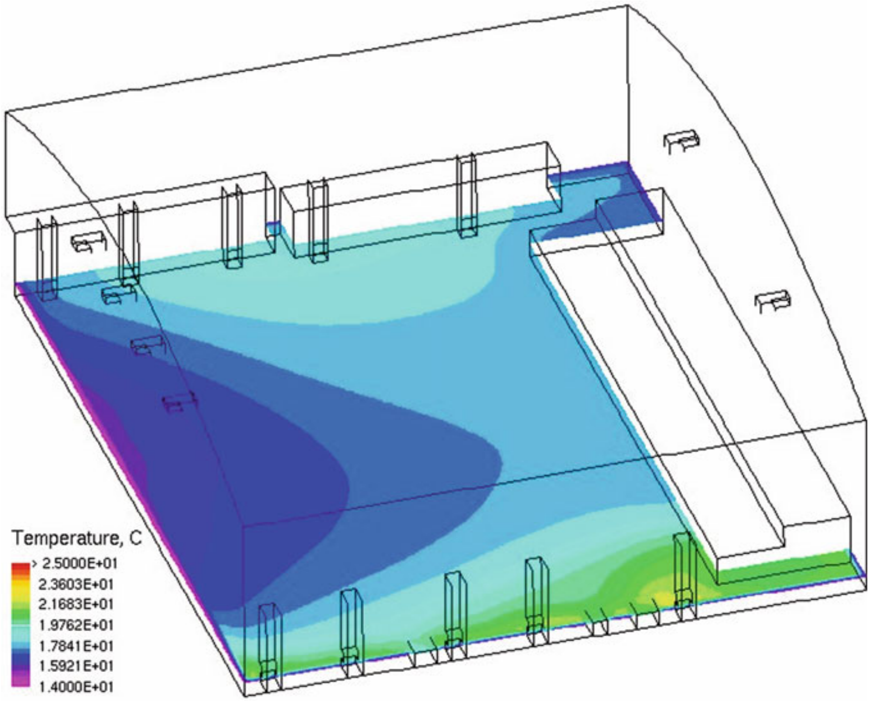


Fig. 16.4 Temperature distribution at 1 m above ground level. The coldest air is close to the ground (stratification). The precise distribution is determined by air currents from doors, windows, and other openings or devices such as fans or heaters

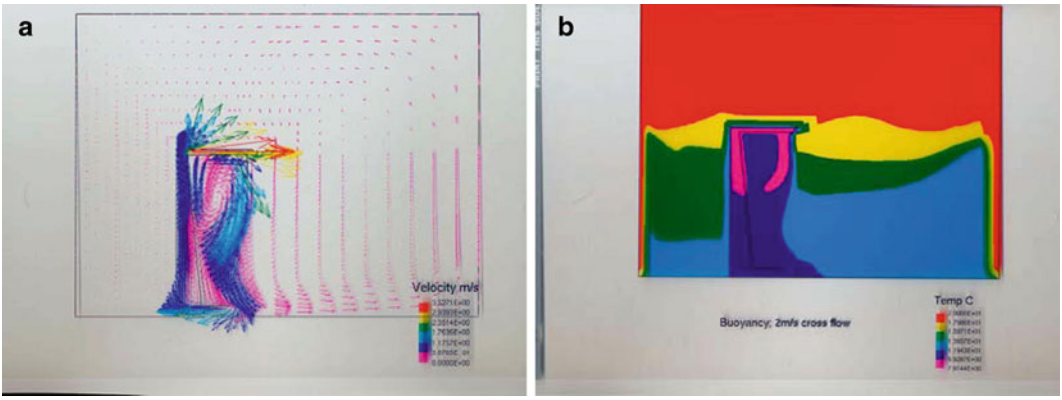


Fig. 16.5 The (**a**) velocity and (**b**) temperature distributions set up as a result of the display cabinet. Note the significant volume of cold air in front of the cabinet

distributions in a very large warehouse/store. In this example, CFD is sufficiently versatile as to enable the prediction of the air currents, which arise from an open doorway. Another example is demonstrated in Figs. 16.5 and 16.6, which depict a chilled display cabinet in a large room. The envelope of cold air is “dropping out” of the cabinet and spilling onto the floor. In supermarkets, this is known as the “cold ankle effect”, which results in minor discomfort and prevents shoppers lingering in front of the cabinets.

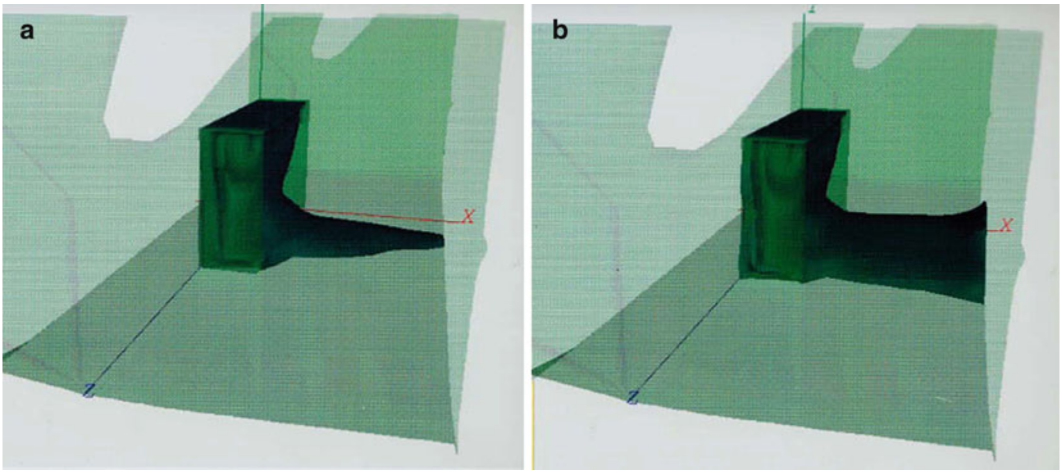


Fig. 16.6 Envelopes enclosing regions surrounding the display cabinet where the temperature is (**a**) 8 °C or lower and (**b**) 9 °C or lower. The food in the cabinet should be at approximately 4 °C. Note the larger floor area covered at 9 °C than at 8 °C

16.5.3 Potential Use of CFD

It is clear from these two relatively simple examples that CFD can be a very powerful tool in specifying design-optimized and customized ventilation systems in food factories. An example of the use of CFD in the food environment can be found in Foster and Quarini (2001). CFD can also be used to study different ventilation philosophies and to assess how these might perform in given food factory environments. For example Kikuchi et al. (2003) have used CFD to compare the relative merit of a ventilation system essentially relying on "sucking" air out of the factory, and thereby allowing a slow ingress of air from potential entry points, and one based on injecting air into the factory. This latter method of ventilation has the advantage of being able to focus air into specific zones but suffers from the potential disadvantage of promoting air movement. Air curtains tend to fall into this category; they can be very effective in engineering required environmental conditions, but can also result in enhanced mixing and higher associated energy costs (from mechanical power consumption and thermal degradation).

When systems and choices are as complex as those studied by Foster and Quarini (2001) and Kikuchi et al. (2004), CFD may be the only sensible self-consistent way of analyzing the situation.

16.6 Example Using Analytical Methods and Correlations to Obtain Estimates for the Required Ventilation to Control Temperature, Humidity, AND Condensation

16.6.1 Achieving Thermal Comfort

Thermal comfort is subjective, but is essentially associated with the body being able to maintain its desired 37 °C temperature. The metabolic rate of a person varies greatly depending on his/her current activity and the health of the individual concerned. An average value is about 75 W. For the body to comfortably regulate its temperature it needs to be able to generate all the heat required to keep it at 37 °C whilst, at the same time, easily loosing energy at the required rate to the environment, if it overheats. The rate of heat loss will depend on the air and the surrounding environmental temperature as well as the air flow rate and humidity. Organizations such ASHRAE in the USA and CIBSE in the UK have defined "effective" or "dry resultant" temperatures in an attempt to specify a representative temperature, which somehow encompasses the effects of forced flow, radiation loss, and humidity. For example, the CIBSE dry resultant temperature, T_c is given by:

$$T_c = \frac{T_r + T_a\sqrt{10V}}{1 + \sqrt{10V}}, \tag{16.9}$$

where T_r and T_a are the radiant and air temperatures (in °C) and V is the air flow (in m/s). The CIBSE specification for T_c excludes any humidity effects as it has been found that when the relative humidity is between 40 and 70 %, T_c, as defined above, is a good working figure to judge whether an environment will be perceived as thermally comfortable or not. The CIBSE recommendations for dry resultant temperatures to achieve comfortable conditions are 13, 15, and 18 °C for heavy work in factories, shops and stores, and lecture halls/churches/exhibition halls, respectively, and 20, 22, and 26 °C for offices, bathrooms, and swimming halls. More data may be found for T_c in CIBSE (1986). It can be observed that, for a typical air speed of 0.1 m/s, which is representative of many domestic/commercial situations, (16.9) simplifies to:

$$T_c = \frac{T_r + T_a}{2}. \tag{16.10}$$

The radiant temperature, T_r can be difficult to measure, and hence an effective internal environmental temperature, T_{ei}, is defined as the temperature which, in the absence of incident radiation, would give the same rate of heat transfer through the external fabric of the room/building as exists with the actual air temperature and incident radiation on the internal surfaces. It can be shown that with reasonable assumptions for heat transfer coefficients within a room, the environmental temperature can be approximated by:

$$T_{ei} = \frac{1}{3}T_a + \frac{2}{3}T_r, \tag{16.11}$$

giving a dry resultant temperature of

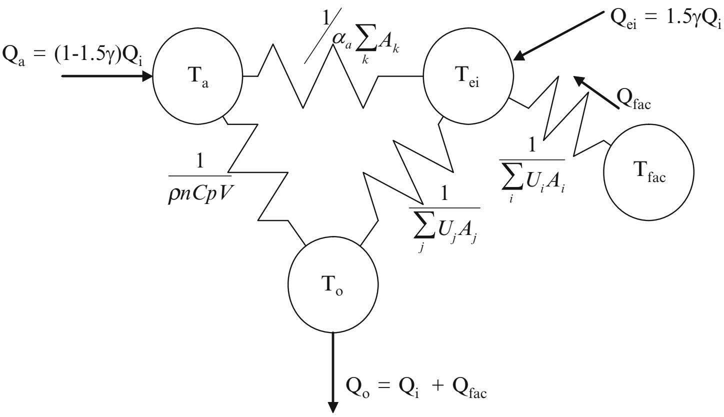
$$T_c = \frac{3}{4}T_{ei} + \frac{1}{4}T_a. \tag{16.12}$$

It is now possible to relate the air and environmental temperatures, T_a and T_{ei}, inside a room to the outside temperature, T_o, and the imposed ventilation, as well as computing the dry resultant temperature, T_c, which determines "comfort". The air temperature is related to the internal environmental temperature via an effective heat transfer coefficient, α_a, so that the rate of heat transfer between the air and the "environment" is

$$\alpha_a \sum A(T_{ei} - T_a). \tag{16.13}$$

Here A is the effective coupling area between the room and the outside. A typical value for α_a is 4.5 W/m^{2}K.

Fig. 16.7 An electrical network analogy of the thermal flow paths for the office to factory to outside



16.6.1.1 Example for Comfort Management

The administrative/finance offices are located adjacent to the factory floor, and have one external wall with 20 % of the area covered by windows. It may be assumed that there are no heat leaks at the ceiling or floor, but that there is thermal coupling to the factory through the partition wall having a thermal transmittance of 0.8 W/m^{2}K. The factory manufactures dairy products and has an average temperature of 10 °C. The outside temperature is 0 °C in winter and the thermal transmittance of the windows and external walls are 4.0 and 0.5 W/m^{2}K, respectively. If the offices have a width and height of 5 and 3 m respectively, and the ventilation system provides two air changes per hour of fresh outside air, calculate the energy (heat) required per meter length of office to keep the inside air temperature, T_a, at 20 °C, when the steel panel radiators provide a radiant component, γ, equal to 15 % of the total heat output. Also compute the dry resultant temperature, T_c.

Take the density and specific heat of air as 1.2 kg/m^3 and 1,000 J/kgK, respectively.

This problem may be tackled by using the standard steady state equations, or by developing an electrical analogy of the system (Fig. 16.7) and then solving for the required quantities. In this figure, for unit length:

$$\Sigma UA = (4 \times 0.2 + 0.5 \times 0.8) \times 3 = 3.6\,\mathrm{W/K}\ (\text{outside wall/window}).$$

$$\Sigma UA = 0.8 \times 1 \times 3 = 2.4\,\mathrm{W/K}\ (\text{office-factory wall}).$$

$$\rho nCpV = 1.2 \times 2 \times 1000 \times (5 \times 3 \times 1)/3600 = 10\mathrm{W/K}.$$

The energy required to heat the ventilation air $= \rho n\mathrm{Cp}V(T_a - T_o) = 10 \times (20 - 0) = 200\,\mathrm{W}$.

For the exchange between the internal air and the environment, the total area of the office walls is required:

$$\Sigma A = 2 \times (5 \times 1 + 3 \times 1)\ \text{per unit length} = 16\,\mathrm{m}^2,$$

and

$$\alpha_a \Sigma A = 4.5 \times 16 = 72\,\mathrm{W/K}.$$

The above system reduces to three simultaneous equations.

At the T_a node:

$$(1 - 1.5 \times \gamma)Q_i + \alpha_a \sum_k A_k(T_{ei} - T_a) + \rho n \mathrm{Cp} V(T_o - T_a) = 0. \tag{16.14}$$

At the T_{ei} node:

$$1.5 \times \gamma Q_i + \alpha_a \sum_k A_k(T_a - T_{ei}) + \sum_{\text{factory}} U_j A_j(T_f - T_{ei}) + \sum_{\text{outwall}} U_i A_i(T_o - T_{ei}) = 0. \tag{16.15}$$

At the T_0 node:

$$-Q_i - \sum_{\text{factory}} U_j A_j(T_f - T_{ei}) + \alpha_a \sum_k A_k(T_{ei} - T_a) + \rho n \mathrm{Cp} V(T_o - T_a) = 0. \tag{16.16}$$

Solving these equations yields $T_{ei} = 19.6\ °\mathrm{C}$ and $T_c = 19.7\ °\mathrm{C}$, indicating that these temperatures are very close to the air temperature, $T_a = 20\ °\mathrm{C}$. The energy required to maintain these temperatures, $Q_i = 294$ W/m. The perceived temperature, T_c is slightly lower than the actual air temperature, because of the radiative effects of the walls, which are cooler than T_a.

One way of increasing the perceived temperature, without increasing the energy load, is to use a form of heating that provides a larger proportion of radiative to convective heating. For example, if, in this case, γ were to be increased from 15 to 50 %, then T_c would increase to 21.3 °C with only a very minor increase in $Q_{i.}$ Indeed, within limits, it is possible to reduce energy consumption without compromising T_c values by moving from a convective to a radiative heat source.

16.6.1.2 Temperature, Humidity, and Contaminant Control

Appendix 1 provides equations that describe the evolution of the concentration of passive scalars in a defined environment. This can be a good starting point from which to estimate the required ventilation to ensure that the building/environment will perform within legislative requirements during transient operations. This could be something as simple as estimating the temperature swings within a factory as a result of shift and activity changes to the more complex problem of computing air-borne particulate and aerosol concentrations resulting from infrequent, but major emptying/filling operations, as might occur when emptying flour silos.

As an example, consider the mean temperature–time evolution that might occur in a cold room, when the doors are left open for a period of time to enable a stacker truck to load/unload material. In Appendix 1, the following equation:

$$T - T_a = \frac{W}{(\rho n V \mathrm{Cp} + UA)}\left[1 - \exp\left\{-t\left(n + \frac{UA}{\rho V \mathrm{Cp}}\right)\right\}\right] + (T_o - T_a)\exp\left\{-t\left(n + \frac{UA}{\rho V \mathrm{Cp}}\right)\right\}, \tag{16.17}$$

is derived; it gives the variation of temperature T as a function of time t (see the Appendix for a full definition of the symbols). This can be extended and generalized to situations where there are more than one ventilation sources and more than one set of heat-transferring walls. Specifically,

$$T = \frac{X}{Y}\left[1 - \exp\left(-t\frac{Y}{\rho V\mathrm{Cp}}\right)\right] + T_0 \exp\left(-t\frac{Y}{\rho V\mathrm{Cp}}\right)$$

where (16.18)

$$X = \rho\mathrm{Cp}\sum_i Q_\mathrm{i}T_\mathrm{i} + W + \sum_j U_\mathrm{j}A_\mathrm{j}T_\mathrm{j} \quad \text{and} \quad Y = \rho\mathrm{Cp}\sum_i Q_\mathrm{i} + W + \sum_j U_\mathrm{j}A_\mathrm{j}.$$

where T_0 is the initial temperature in the store room. If boundary conditions are altered during the transient, such that new sources or sinks arise at time $t = t_1$, then, a similar expression is valid, with appropriate new values of X_1 and Y_1, i. e.

$$T(t > t_1) = \frac{X_1}{Y_1}\left[1 - \exp\left(-\tau\frac{Y_1}{\rho V\mathrm{Cp}}\right)\right] + T_1 \exp\left(-\tau\frac{Y_1}{\rho V\mathrm{Cp}}\right)$$

where (16.19)

$$\tau = t - t_1 \text{ and } T_1 = T(t = t_1).$$

16.7 Example of Transient Temperature Excursions

A large 1,000 m^3 cold store has to be maintained at temperatures between −25 and −20 °C. The refrigeration plant can supply cold air at −40 °C up to a maximum flow rate of 1,000 m^3/h. The total vertical wall area is 280 m^2; the ceiling and floor areas are both 250 m^2. The outside temperature is 20 °C, while the ground temperature (under the store) is 5 °C. All floors and walls and the ceiling have been well insulated with resultant U (thermal transmittance) values of 0.05, 0.1 and 0.15 W/m^{2}K, respectively. Compute the minimum temperature the store could be operated at and the flow rate needed to maintain the store at between −25 and −20 °C.

A door is left open for time t hours to allow stock movements. Open doors result in an effective volumetric air exchange of 200 m^3/h of warm 20 °C air from the outside. If the store was initially at −25 °C, estimate the time the door can be left open for before it starts to run outside its specification.

In the first part of this example, the store operates at steady state. It follows from (16.18) that, when t is very large:

$$T = \frac{X}{Y} \quad X = \rho\mathrm{Cp}\sum_i Q_\mathrm{i}T_\mathrm{i} + W + \sum_j U_\mathrm{j}A_\mathrm{j}T_\mathrm{j} \quad Y = \rho\mathrm{Cp}\sum_i Q_\mathrm{i} + W + \sum_j U_\mathrm{j}A_\mathrm{j}. \qquad (16.20)$$

Substituting the appropriate values for ρ, Cp, etc. into (16.20) yields $X = -11{,}960$ W, $Y = 411$ W/K and $T = -29.1$ °C, which is colder than required. Rearranging the expressions to find Q for a store temperature of –25 °C yields $Q = 664.5$ m^3/h.

With infiltration, the complete form of (16.17) has to be used. Solving for T at various times, t, after infiltration starts shows that the temperature in the store does indeed rise, reaching −20 °C approximately 0.85 h after the doors have been opened (see Fig. 16.8).

This method could also be used to estimate the extra refrigeration load needed to cope with the open door while still maintaining the temperature within the store at acceptable levels.

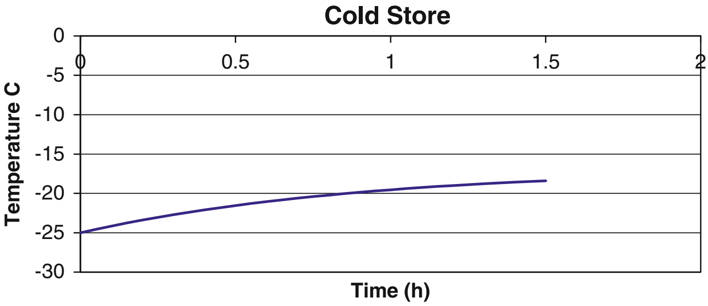


Fig. 16.8 Temperature of the air in the cold store after the door has been opened and infiltration has begun

16.8 Onset and Prevention of Condensation

16.8.1 Basic Equations

The variation of mean humidity, H, defined as mass of water vapor per unit mass of carrier air, in an enclosed volume V, with imposed ventilation of n volume changes per unit time, t, is given by:

$$(H - \mathrm{Ho}) = \left\{ \mathrm{Ha} - \mathrm{Ho} + \frac{\mathrm{Mp}}{\rho n V} \right\} \{1 - \exp(-nt)\}, \tag{16.21}$$

where Mp is the vapor generation rate and Ho and Ha are the initial humidity in the volume and of the current ventilation air, respectively. A full derivation of this equation is provided in Appendix 1. It can be extended to deal with situations where there are multiple infiltrations of air at volume flows Q_i with humidity $\mathrm{Ha_i}$ and multiple sources of water vapor, $\mathrm{Mp_j}$, to yield:

$$(H - \mathrm{Ho}) = \left\{ \frac{\sum_i Q_\mathrm{i}\mathrm{Ha_i} + \sum_\mathrm{j} \frac{\mathrm{Mp_j}}{\rho}}{\sum_i Q_\mathrm{i}} - \mathrm{Ho} \right\} \left\{ 1 - \exp\left(-t \frac{\sum_i Q_\mathrm{i}}{V} \right) \right\}. \tag{16.22}$$

With the other analytical expressions provided in Appendix 1, it is possible to estimate the variation of temperature as well as humidity with time. A knowledge of the saturation vapor pressure will then enable a prediction to be made as to whether condensation is likely to occur and, perhaps more importantly, what ventilation rates will be needed to avoid the phenomenon. This is perhaps best illustrated with a simple example of condensation occurring on a cold surface; this surface could be a window, a poorly insulated wall, or cold water pipes running through a warm damp factory.

Condensation will tend to occur when humid air is cooled to a temperature at which the relative humidity at the coldest point approaches and then exceeds 100 %. This situation can and often does occur in badly designed environments. It is possible to reduce and even eliminate condensation problems by forced ventilation, but it is also possible to exacerbate the situation if the ventilation strategy has not been properly though through.

16.8.1.1 Condensation Example

Consider a large sauce production room of volume 500 m^3. During the day the operating temperature reaches 25 °C with a relative humidity of 55 %. At weekends, there is no production and the temperature of the room is allowed to fall at a rate of 1 K/h (this rate of temperature decrease could

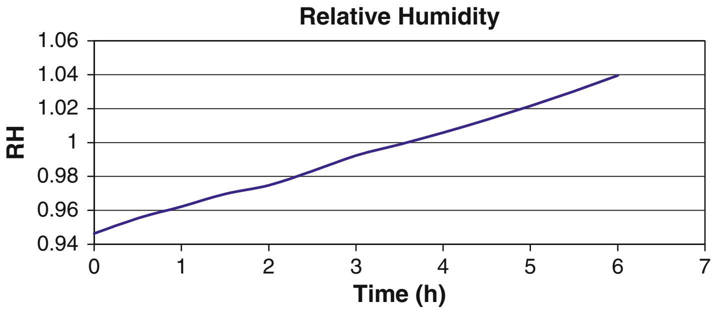


Fig. 16.9 Plot of relative humidity of the air adjacent to the inside surface of the window during cool down

be determined by the methods shown above or by using the equations in Appendix 1). Ventilation is maintained, but at a relatively low rate of 20 m^3/h. The ventilation air is taken from outside where the temperature is 2 °C and the relative humidity is 90 %. The coldest points in the room are the windows, which have a thermal transmittance of 5 W/m^{2}K, an internal heat transfer coefficient of 8 W/m^{2}K and a very large external coefficient. It is now possible to estimate how long it will take for condensation to start to occur on the windows, and also to devise policies which would prevent the formation of condensate. To do this we need to evaluate the temperature of the inside surface of the window, T_s as a function of time. This is simply given by:

$$T_s = \frac{\alpha T_r + (k/\Delta x)T_o}{\alpha + (k/\Delta x)}, \tag{16.23}$$

where T_r and T_o are the room and outside temperatures. For this specific example,

$$T_s = \frac{8T_r + 5 \times 2}{8 + 5} = \frac{8T_r + 10}{13}.$$

The vapor pressure, p_v, in the room can be computed from the relative humidity, RH, by looking up the saturation vapor pressure, p_{vs}, in steam tables for the temperature T_r.

$$\mathrm{RH} = \frac{p_v}{p_{vs}}. \tag{16.24}$$

Now from steam tables (e.g., Rogers and Mayhew 1995), $p_{vs} = 0.03166$ bar, and so $p_v = 0.7 \times 0.03166 = 0.022162$ bar. Once the vapor pressure has been evaluated, the humidity simply follows from (see Appendix 2):

$$H = 0.622 \frac{p_v}{(p - p_v)}. \tag{16.25}$$

The evolution of H with respect to time is predicted using Ho = 1.01087, Ha = 0.03933, and n = 5,000/20 = 0.04 (1/h), i.e.,

$$H = \mathrm{Ho} + \{\mathrm{Ha} - \mathrm{Ho}\}\{1 - \exp(-nt)\}$$

$$H = 0.01087 + (0.03933 - 0.01087)(1 - \exp(-0.04t)),$$

from which the water vapor pressure in the room, p_v, is computed. The saturation vapor pressure at the window, p_{vs}, at temperature T_s is found from steam tables and the relative humidity computed from these two quantities. When the relative humidity attains 100 %, condensation starts. The computations suggest that this occurs about 3.7 h after the cool down is initiated (see Fig. 16.9).

The same technique can be used to estimate the ventilation flows required to ensure that condensation does not occur, or the required value of thermal conductivity of the window to guarantee that its temperature is always sufficiently high to ensure that the adjacent air never becomes saturated.

16.8.2 Some Practical Engineering Issues

16.8.2.1 Influent Air Quality

It is important to ensure that the quality of the air introduced into the working areas is fit for purpose. In many cases air taken from the outside, once heated/cooled and brought to the correct humidity, is adequate. However, there are situations where even minor atmospheric contaminants have to be removed or reduced to acceptable levels. These contaminants may include dusts, fumes, smokes, mists, vapors, and organic particles. The level of air quality required as well as the capital and running costs that can be afforded will determine the types of filtration device that should be adopted. British Standard (BS EN 779 1993) classifies filter types and provides expected efficiencies and evaluation methodologies for them. The terms HEPA (High Efficiency Particulate Air) and ULPA (Ultra Low Penetration Air) are used to describe filters capable of removing 95–99.999 and 99.9995–99.999995 % of particulates of 0.3 μm diameter, respectively, from the air stream passing through them. As the efficiency of the filter increases, the permitted through flow of air decreases and the pressure loss increases. These trends translate into higher capital and running costs. The highest efficiency, ULPA filters tend to be used for very specific applications requiring either very high gas purity or where there is a need to guarantee containment levels, as may occur in the pharmaceutical industries. BS EN 779 (1993) provides specific classifications for the various classes of HEPA and ULPA filters.

There are a variety of commercial filters to choose from; the manufacturers will provide characterization specifications, which will detail expected pressure losses, recommended flow velocities, and efficiency as a function of particle size. Basically there are six types of filtration devices available. The simple dry filter consists of a fibrous material (cotton wool, glass fiber, fabrics, pleated paper, cellular plastics, etc.) that “filters out” by straining or interception the particles carried by the air. There are numerous topologies and layouts for such devices, including bags and panels. The term “viscous filter” is given to filters where the filter medium is covered with a suitable oily fluid, making the trapping and removal of the impinging particles more efficient. Electrostatic filters work by imparting an electrical charge to the particles as the air flows through the ionizing field set up within the filter. The charged particles are then more easily removed/collected on conducting plates with charges opposite to those carried by the particles or simply grounded plates. Electrostatic filters should give rise to lower pressure drops than either the dry or viscous filters. Washers and scrubbers are sometimes appropriate, especially if the pollutants are undesirable gases such as sulfur dioxide or chlorine. Centrifugal collectors (cyclones) tend to be adopted as the preferred means of removing dust from industrial exhausts rather than a means of cleaning environmental air prior to supplying it to the air conditioning system. The last form of filtration available commercially relies on adsorption. Adsorption is a physical process (Robinson and Quellet 1999) whereby relatively high boiling point gases are retained at ambient temperatures by certain materials such as activated carbon or zeolites. For example, activated carbon is very effective at adsorbing putrescine and common mercaptans, which can give rise to the “bad odors” associated with rotting organic matter including proteins and fats.

16.8.3 Conditioning Air

As well as heating/cooling air to the required temperatures, there may also be a need to condition it so as to obtain an acceptable humidity level. Air heating can be achieved using a variety of means including hot water and steam coils, direct gas firing, or electrical resistance heating elements. The exact choice will depend on availability, convenience and cost.

The temperatures (dry and wet bulb) and relative humidity of a given mass of air are coupled in that the application of heat to an isolated system will both increase the temperature and reduce the relative humidity. Systems employed to "engineer" required or desirable conditions include water spraying into unsaturated air. This reduces the temperature and increases the humidity. Steam injection can be used to increase the humidity without cooling the air. Air washing with chilled water is used to reduce the temperature of the air. The equipment used to condition air includes evaporative or desert coolers (which essentially draw air over a wetted pad and discharge it into the conditioned space), cooling towers and evaporative condensers. A cooling tower is an evaporative cooler whose prime purpose is to cool water rather than condition air.

Those involved in air conditioning should become familiar with psychometric charts, which provide graphical representations of the dependence of wet and dry bulb temperatures, specific enthalpy, moisture content, and percentage saturation on a single chart. Details can be found in many chemical and mechanical engineering texts—see for example Genskow et al. (2008).

16.8.4 Engineering Air Movement

The typical driving pressure difference required for air conditioning systems is rarely in excess of a few percent of a bar (one atmosphere); hence dynamic air-moving machinery rather than positive displacement devices are used to provide the required air circulation. The most common device for this is a centrifugal fan, which, as the name suggests, pumps air by developing a centrifugal driving force in its working section. This centrifugal force varies with the square of the rotation speed, and hence so does the pressure difference it is able to develop. As the volume flow rate varies linearly with speed, the power consumed by the fan is proportional to its rotation speed cubed. Since the resistance to turbulent flow in ducts is proportional to the flow squared, changing the rotational speed of a centrifugal fan provides an almost linear change of air flow rate. Furthermore, at stall, the fan will absorb little power (the limited consumption being used for local internal turbulence generation.). If higher pressures are required, they may be achieved by placing two fans in series. Manufacturers will provide fan characteristics and recommendations for optimal operating conditions.

One of the problems associated with circulating large quantities of air is noise. Much of this can be generated within the fan. Care must therefore be taken to acoustically insulate the fan/motor assembly. Using flexible connectors and mounting the fan assembly on vibration-absorbing devices can achieve acceptable attenuation of noise levels. The fans themselves should be regularly rebalanced to reduce the degree of self imposed mechanical vibration.

Noise is also generated by air flow in delivery and distribution ducts. The flow rates and size of ducts implies that nearly all air flows in air-conditioning systems are in the turbulent regime. A high duct velocity will reduce the capital cost of the duct, but increase the power requirements and generate more noise. Typical high velocity air flows will be around 20 m/s, while low velocities employed in main ducts will be around 10 m/s. For ducts in quiet areas, the flow speeds should be at or below 3–4 m/s.

Using friction factors (or/and appropriate charts) it is possible to deduce the friction pressure loss within the duct work, and hence specify the power required from the fan to ensure adequate ventilation. In some cases it is as important to ensure that the flow within complex duct work is correctly balanced as it is to ensure that the absolute flows are at the required values. In these cases, it is important that the relative pressure losses incurred as the flow goes through bends, contractions/ expansions, and other ancillary components (diffusers, dampers) are known. In practice, most equipment suppliers and installation contractors perform duct sizing, layout design and fan specification calculations using customized computer programs. Nonetheless, as illustrated below, it is possible to do a quick manual sizing to give preliminary designs.

Example 1 A centrifugal fan is used to deliver a total of 6 m^3/s of air (density $\rho = 1.2\ kg/m^3$) to two store rooms. One room (No. 1), located 20 m from the fan, has to receive twice the air flow of the other (No. 2), which is 10 m from the fan. Assume the pressure loss due to friction along the duct is given by:

$$\Delta P_{\text{friction}} = K_1 \rho U^2 L/D,$$

where K_1 is a friction factor $= 0.02$, L and D are the length and diameter of the duct, and U is the flow velocity in the duct. Deduce the relative sizes of the ducts required to achieve the desired distribution without the need for dampers.

If the air velocity cannot exceed 3 m/s (to avoid noise problems), deduce the power requirements of the fan. Assume that the fan/motor efficiency (ratio of air power/electrical power) is 60 %.

The volume flows in the ducts are 2/3 and 1/3 of 6 m^3/s respectively, and the velocities are given by

$$\frac{\pi}{4} {D_1}^2 U_1 = V_1 \text{ and } \frac{\pi}{4} {D_2}^2 U_2 = V_2,$$

where V_1 and V_2 are 4 and 2 m^3/s, respectively. Similarly the frictional pressure losses are, from above:

$$\Delta P_{\text{friction}1} = 0.02\rho \left(\frac{4V_1}{\pi {D_1}^2}\right)^2 \left(\frac{L_1}{D_1}\right) \text{ and } \Delta P_{\text{friction}2} = 0.02\rho \left(\frac{4V_2}{\pi {D_2}^2}\right)^2 \left(\frac{L_2}{D_2}\right).$$

If the friction pressure loss is to be the same in both ducts, then simple algebraic manipulation gives:

$$\left(\frac{D_1}{D_2}\right)^5 = \left(\frac{V_1}{V_2}\right)^2,$$

yielding $D_1/D_2 = 1.516$

With the deduced ratio $D_1/D_2 = 1.516$, the 3 m/s velocity limit is reached in smaller diameter duct first. The pressure loss (equal for both ducts) is therefore:

$$\Delta P_{\text{friction}} = 0.02\rho 3^2 10/D_1,$$

where D_1 is computed from the volume balance

$$D_1 = \left(\frac{4V_1}{\pi u_1}\right)^{0.5} = \left(\frac{4 \times 2}{\pi \times 3}\right)^{0.5} = 0.84 \text{ m}.$$

Hence, the frictional pressure loss = 2.57 N/m^2 and the air power = 2.57 × 6 = 15.4 W. This corresponds to an electrical power demand of 15.4/0.6 = 25.7 W.

This is a relatively low power requirement, because the calculations indicate that that the pressure losses are very small. Indeed, this is normally the case unless the duct work is particularly long or incorrectly sized. In many cases the inertial losses that occur when the air enters and leaves the duct and flows around corners tend to dominate, as can be seen from the following example.

Example 2 Repeat the above calculations assuming that the entry and exit losses to the duct work are of the form:

$$\Delta P_{\text{entry/exit}} = K_2 \rho U^2,$$

where K_2 is a constant = 4.

To simplify the computations, we will assume (rightly as shown below) that frictional losses are negligible. In this case the pressure losses in the two ducts are:

$$\Delta P_{\text{entry/exit}} = 4\rho {U_1}^2 = 4\rho \left(\frac{4 \times 4}{\pi {D_1}^2}\right)^2 = 4\rho \left(\frac{2 \times 4}{\pi {D_2}^2}\right)^2,$$

giving $D_1/D_2 = 1.414$.

Hence D_1 and D_2 equal 1.19 and 0.84 m respectively. The pressure loss due to the entry/exit is therefore $(4 \times 1.2 \times 3^2) = 43.2 \text{ N/m}^2$ and the air power = 43.2 × 6 = 260 W, corresponding to an electrical power demand of 260/0.6 = 432 W.

This calculation clearly indicates the dominating effect that inertial losses can have on the flow distribution within an air conditioning duct work system. In this case, the example suggests that the power requirements to overcome inertial losses are 18 or so times greater than those required to overcome frictional losses.

16.9 Summary

Ventilation is one of the most important facets in the determination of efficient, safe, and profitable food factory operation. In this chapter we have identified the drivers (personal comfort, product safety and shelf-life extension, energy efficiency and factory flexibility), which will continue to force factory designers to devote ever increasing resources and attention to the optimization of appropriate ventilation systems. We then provided information on how initial estimates of ventilation requirements can be made. These methods are expanded in the Appendices 1 and 2. A flavor of some of the more advanced methods, in particular CFD, has been presented.

The aim of the chapter is to provide an introduction to the complex area of ventilation. It also provides a number of references, which give the current regulatory recommendations for ventilation. Using the Appendices 1 and 2, the reader should be able to undertake simple calculations in order to estimate the ventilation requirements for his/her specific factory.

Appendix 1: Derivation of Transient Temperature, Humidity, and Pollutant Concentration Equations

A.1 Transient Temperature

Consider a room of volume V, with an air exchange rate of Q m^3/s. An enthalpy balance on the room yields:

Rate of change of enthalpy = Heat in/out + Energy generation + Heat transfer to room.

$$\rho V\mathrm{Cp}\frac{\mathrm{d}T}{\mathrm{d}t} = \rho Q\mathrm{Cp}\,(T_\mathrm{a} - T) + W + UA(T_\mathrm{a} - T), \tag{16.26}$$

where T and T_a are the temperatures (K) of the room and outside air respectively, t is time (s), Cp and ρ are the specific heat (J/kgK) and density (kg/m^3) of the air, W is the rate of heat generation inside the room (W), U is the effective heat transfer coefficient (W/m^{2}K) between the air in the room and that outside, and A is the effective coupling area (m^2) between the room and outside. Rearranging (16.26) yields:

$$\frac{-\mathrm{d}T}{(W/\rho Q\mathrm{Cp} + UA) + (T_\mathrm{a} - T)} = -\mathrm{d}t\left(\frac{Q}{V} + \frac{UA}{\rho V\mathrm{Cp}}\right). \tag{16.27}$$

Integrating (16.27):

$$\ln\left\{\frac{W}{(\rho Q\mathrm{Cp} + UA)} + (T_\mathrm{a} - T)\right\} = \left[-t\left(\frac{Q}{V} + \frac{UA}{\rho V\mathrm{Cp}}\right) + \mathrm{Constant}\right]. \tag{16.28}$$

Let the initial temperature of the air in the room be T_0. The boundary condition is then $T = T_0$ at $t = 0$. Equation (16.28) then reduces to

$$T - T_\mathrm{a} = \frac{W}{(\rho Q\mathrm{Cp} + UA)}\left[1 - \exp\left\{-t\left(\frac{Q}{V} + \frac{UA}{\rho V\mathrm{Cp}}\right)\right\}\right] + (T_0 - T_\mathrm{a})\exp\left\{-t\left(\frac{Q}{V} + \frac{UA}{\rho V\mathrm{Cp}}\right)\right\}. \tag{16.29}$$

The number of air changes per second is $n = Q/V$. Hence (16.29) can be written:

$$T - T_\mathrm{a} = \frac{W}{(\rho nV\mathrm{Cp} + UA)}\left[1 - \exp\left\{-t\left(n + \frac{UA}{\rho V\mathrm{Cp}}\right)\right\}\right] + (T_0 - T_\mathrm{a})\exp\left\{-t\left(n + \frac{UA}{\rho V\mathrm{Cp}}\right)\right\}. \tag{16.30}$$

which, for steady state, or as t tends to infinity, reduces to

$$T - T_\mathrm{a} = \frac{W}{(\rho Q\mathrm{Cp} + UA)} = \frac{W}{(\rho nV\mathrm{Cp} + UA)}. \tag{16.31}$$

A.2 Transient Humidity

Consider a room of volume V, with an air exchange rate of Q m^3/s. A mass balance on the water vapor entering and leaving the room yields:

Rate of change of humidity in room = Humidity transported in/out + Amount generated

$$V\mathrm{d}H/\mathrm{dt} = Q(\mathrm{Ha} - H) + \mathrm{Mp}/\rho, \tag{16.32}$$

where H and Ha are the humidities (kg H_2O/kg dry air) of the room and outside air, respectively, and Mp is the moisture production rate (kg H_2O/s). Rearranging (16.32) yields:

$$(-\mathrm{d}H)/(\mathrm{Ha} + \mathrm{Mp}/Q\rho - H) = (-\mathrm{d}t)/VQ. \tag{16.33}$$

Integrating (16.33) with the boundary condition $H = \mathrm{Ho}$ at $t = 0$ and substituting $n = Q/V$ yields:

$$(H - \mathrm{Ho}) = \{\mathrm{Ha} - \mathrm{Ho} + \mathrm{Mp}/\rho nV\}\{1 - \exp(-nt)\}. \tag{16.34}$$

A.3 Transient Pollutant

Consider a room of volume V, with an air exchange rate of Q m^3/s. A mass balance on the pollutant entering and leaving the room yields:

$$\begin{aligned}&\text{Rate of change of pollutant concentration in room}\\&\quad = \text{Pollutant convected in/out} + \text{Emissions} - \text{Removal}\end{aligned}$$

$$V\frac{\mathrm{d}C}{\mathrm{dt}} = QC_{\mathrm{a}} + E - QC - kCV \tag{16.35}$$

where C and C_{a} are the pollutant concentrations (kg pollutant/kg dry air) of the room and outside air, respectively, E is the emission rate (kg/s), and k is the removal rate (1/s) of the pollutant in the room. Rearranging and integrating (16.35) with the boundary condition $C = C_{\mathrm{o}}$ at $t = 0$ yields:

$$\begin{aligned}C &= \left(\frac{QC_{\mathrm{a}} + E}{Q + kV}\right)\left\{1 - \exp\left(-\left(\frac{Q}{V} + k\right)t\right)\right\} + C_{\mathrm{o}}\exp\left(-\left(\frac{Q}{V} + k\right)t\right)\\ &= \left(\frac{nC_{\mathrm{a}} + E/V}{n + k}\right)\{1 - \exp(-(n + k)t)\} + C_{\mathrm{o}}\exp(-(n + k)t).\end{aligned} \tag{16.36}$$

At steady state,

$$C = \frac{QC_{\mathrm{a}} + E}{Q + kV} = \frac{nC_{\mathrm{a}} + E/V}{n + k}. \tag{16.37}$$

Also, if k tends to zero and the air outside is "clean" ($C_{\mathrm{a}} = 0$), then for $C_{\mathrm{o}} = 0$

$$C = \frac{E}{Q}\left\{1 - \exp\left(-\frac{Q}{V}t\right)\right\} = \frac{E}{nV}\{1 - \exp(-nt)\}. \tag{16.38}$$

Appendix 2: Humidity and Condensation

The terms humidity and relative humidity have specific definitions in psychrometry. These are:

Humidity, *H*, is the ratio of the mass of water vapor per unit mass of dry air,

and,

Relative Humidity, *RH*, is the ratio of partial vapor pressure, p_{v} to the saturation vapor pressure, p_{vs}, at the same temperature.

$$\begin{gathered} H = \frac{M_{\mathrm{water}} p_v}{M_{\mathrm{air}}(p - p_{\mathrm{v}})} = \frac{18 p_{\mathrm{v}}}{29(p - p_{\mathrm{v}})} = 0.622 \frac{p_{\mathrm{v}}}{(p - p_{\mathrm{v}})} \\ \mathrm{RH} = \frac{p_{\mathrm{v}}}{p_{\mathrm{vs}}} \end{gathered} . \tag{16.39}$$

It follows from the perfect gas law that

$$\begin{gathered} H = \frac{M_{\mathrm{water}} p_{\mathrm{v}}}{M_{\mathrm{air}}(p - p_{\mathrm{v}})} = \frac{18 p_{\mathrm{v}}}{29(p - p_{\mathrm{v}})} = 0.622 \frac{p_{\mathrm{v}}}{(p - p_{\mathrm{v}})} \\ \mathrm{RH} = \frac{p_{\mathrm{v}}}{p_{\mathrm{vs}}} \end{gathered} , \tag{16.40}$$

where M_{water} and M_{air} are the molar masses of water and air respectively, and p, p_{v} and p_{vs} are the total pressure in the room, the water vapor pressure in the room and the water saturated vapor pressure at the room temperature.

Condensation will start to occur when the relative humidity reaches 100 %. The following procedure can be used to predict whether condensation is likely to occur within a ventilated room:

1. Evaluate H and T from the equations given in Appendix 1.
2. From the estimate of T find p_{vs} from steam tables.
3. From the estimate of H compute p_{v}.
4. Compare the vapor pressure values; if $p_{\mathrm{v}} > p_{\mathrm{vs}}$ then condensation will occur.

Normally, condensation will occur on the coldest surfaces when the *local* RH value (this is the RH value computed using the temperature of the cold surface) reaches 100 %. In order to predict the likelihood of condensation on cold surfaces, the same procedure as that identified above can be adopted, using the temperature of the cold surface to estimate p_{vs}, rather than the temperature of the air. The p_{v} is still evaluated using the computed bulk air humidity value, H.

References

Anderson D. A., Tannehill J. C. and Pletcher R. H. (1984) "Computational fluid mechanics and heat transfer", Taylor and Francis, Bristol, PA 19007.

ASHRAE (1999) "Ventilation for acceptable indoor quality", ASHRAE, Atlanta, GA.

BS EN 779 (1993) "Particulate air filters for general ventilation – Requirements, testing, marking", British Standards Institute, London.

CIBSE (1986) "Guide to current practice, Volume 1", The Chartered Institution of Building Services Engineers, London.

CIBSE (2001) "Heating, air conditioning and refrigeration. Guide B2: Ventilation and air conditioning", ISBN 1903287162, The Chartered Institution of Building Services Engineers, London.

Ferziger J. H. and Peric M. (1997) “Computational methods for fluid dynamics”, Springer, New York.

Foster A. M. and Quarini, G. L. (2001) “Using advanced modeling techniques to reduce the cold spillage from retail display cabinets into supermarket stores to maintain customer comfort”, Proceedings of the Institution of Mechanical Engineers, Part E 215, pp. 29–38.

GOV.UK (2013) “Providing effective building regulations so that new and altered buildings are safe, accessible and efficient. Approved Documents Part F (ventilation)”, February, Dept. for Communities and Local Government, London. Available online at www.planningportal.gov.uk/buildingregulations/approveddocuments/partf/.

HMSO (2004) “Review of Approved Document F (Ventilation) – A consultation package”, July, Her Majesty’s Stationary Office, London.

HSE (2011) “Ventilation of kitchens in catering establishments”, Catering Information Sheet No 10 (rev1), Health and Safety Executive, London, August. Available online at www.hse.gov.uk/pubns/cais10.pdf.

HSE (2013) “Health and safety in catering and hospitality”, Health and Safety Executive, London, 11 February. Available online at www.hse.gov.uk/catering/.

Jensen, B.B.B. and Friis, A. (2004) “Prediction of flow in mix-proof valve by use of CFD-validation by LDA”, J. Food Process Engineering, Vol. 27, pp. 65–85.

Jones, W. P. (2001) “Air conditioning engineering”, 5th edit., Butterworth-Heinemann, New York, ISBN 0 75065074 5.

Kikuchi S., Ito K. and Kobayashi N. (2003) “Numerical analysis of ventilation effectiveness in occupied zones for various industrial ventilation systems”. 7th International Symposium on Ventilation for contamination control, Paper PS-9, August 5–8, Hokkaido University, Sapparo, Japan.

Kikuchi, S., Kobayahi, N. and Ito, K. (2004) “Numerical analysis of ventilation effectiveness in occupied zones and its air quality control for various industrial ventilation systems by using push-flow”, Trans Society of Heating, Air Conditioning and Sanitary Engineers of Japan, Issue 92, pp. 65–72.

Genskow, L.R., Beimesch, W.E., Hecht, J.P., Kemp, I.C., Langrish, T., Schwartzbach, C. and Smith, F.L. (2008) “Psychrometry, evaporative cooling, and solids drying”, Section 12 in Green, D.W. and Perry, R.H. (eds) “Perry’s Chemical Engineers’ Handbook”, 8th edit., McGraw Hill, New York, ISBN 978-0-07-142294-9.

Peyret R. (1996) (ed.) “Handbook of computational fluid mechanics”, Academic Press, New York.

Robinson, T.J. and Quellet, A.E. (1999) “Filters and Filtration”, ASHRAE Journal, April, pp. 65–68.

Rogers G. F.C. and Mayhew Y. R. (1995) “Thermodynamic and transport properties of fluids, SI Units”, Blackwell, Oxford, ISBN 0-631-19703-6.

Trott, A. R. and Welch, T. (2000) “Refrigeration and Air-Conditioning”, 3rd edit., Butterworth Heiemann, ISBN 0 75066421 9 X.

Wilcox D. C. (1993) “Turbulence modeling for CFD”, DWC Industries Inc., La Canada, USA.

Chapter 17
Utilities and Their Conservation

A.A. Aly and C.G.J. Baker

17.1 Introduction

Virtually all food-manufacturing processes involve the use of energy (gas, fuel oil, steam, etc.) and water. In many cases, there are significant opportunities for reducing both the usage and cost of these utilities. Such savings can accrue both as a result of effective design and efficient operation. In general, conservation of energy and water has not been high on factory management's list of priorities in the past because these commodities normally account for only a small percentage of the total product cost. However, given that any savings achieved will impact directly on the company's bottom line, they are certainly worthy of consideration. Moreover, the fuel savings achieved will also result in corresponding reductions in greenhouse gas emissions. Food products vary widely in the quantities of fuel and electricity consumed during the course of their manufacture. Values of specific energy consumption for a wide variety of foods have been published by Ramirez et al. (2006).

Three texts on energy and water usage have recently been published that provide extensive coverage of this subject: Encyclopedia of Energy Engineering and Technology, edited by Capehart (2007); Handbook of Energy Efficiency and Renewable Energy, edited by Kreith and Goswami (2007); Handbook of Water and Energy Management in Food Processing, edited by Klemeš et al. (2008). Consequently, this subject will not be covered in depth in the present Handbook.

17.2 Energy

17.2.1 Electricity

The principal end uses of electricity in food manufacturing are machine drives (e.g., conveyors, fans, pumps, etc.), HVAC, lighting, process cooling and refrigeration, and on-site vehicles (e.g., fork lift trucks). Of these, electric motors constitute by far the heaviest load (Smith et al. 2007). According to

---

A.A. Aly
Industrial and Management Systems Engineering Department, Kuwait University,
P.O. Box 5969 Safat, 13060 Kuwait
e-mail: a.aly@ku.edu.kw

C.G.J. Baker (✉)
Chemical Engineering Department, College of Engineering and Petroleum,
Kuwait University, P.O. Box 5969 Safat, 13060 Kuwait
e-mail: christophergj.baker@gmail.com

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_17,

these authors, in 1998, motors accounted for 68.2 % of electricity use by industry, 20.8 % was employed for process use, 6.5 % for lighting, and 4.5 % for other uses. Thus, correct selection of electrically powered plant and equipment at the design stage can result in useful savings during operation. Some examples are given in the following paragraphs.

Smith et al. (2007) listed a number of design factors that can help to reduce power consumption:

1. *Motor oversizing*. As is the case with most equipment design, there is a natural tendency to play it safe by oversizing electric motors. This may be detrimental from the viewpoint of power consumption for two reasons. Firstly, the efficiency of an electric motor operating continuously below 50 % of capacity may be significantly lower than one operating at full capacity. For example, the efficiency of a 1 kW motor operating at 100 % rated load is typically around 70 % whereas that with a 50 % load is around 60 %. Larger motors tend to operate close to peak efficiencies over a wider range of loads but exhibit more drastic reductions below 25 %. Secondly, underloaded motors are often the principal cause of a poor power factor, which decreases progressively as the percent load decreases. Most utility suppliers apply a penalty charge when the power factor is below a stipulated value, typically 0.9–0.95. Note, however, that the installation of compensation capacitors can offset any reduction in power factor.
2. *Cable sizing*. The transmission of an electric current through distribution cables, etc., results in ohmic heating, also known as I^2R losses. These losses may be minimized by correct selection of the conductor leads. The National Electrical Code (NFPA 2008) in the USA and equivalent codes in other jurisdictions specify cable sizes that prevent overheating and allow for an adequate starting current for motors. These should be regarded as the minimum permissible as they are not necessarily energy efficient. Smith et al. (2007) suggested that it was often economical, on a 2-year payback basis, to use cabling one wire size larger than that recommended by the NEC.
3. *Transmissions*. Mechanical energy needs to be transferred efficiently and effectively between the motor and the equipment that is being driven. The available options include direct shaft couplings, gearboxes, chain drives, and belts. Selection of the most appropriate technique depends on a number of factors including required speed ratio, power, layout of shafts, and type of mechanical load. Smith et al. compared the efficiencies of a number of V-belt drives. They noted that standard V-belts have efficiencies in the range 90–96 %; the losses can be attributed mainly to flexing and slippage. The latter tends to increase with time and, unless corrected, results in increased losses. The efficiency of cogged V-belts tends to be some 2–3 % higher than standard V-belts and synchronous V-belts are even more efficient (98–99 %) as there is no slippage and flexing losses are low. The life of these drives is claimed to be double that of a standard V-belt, which more than offsets their added cost.

In many applications, electric motors are used to drive pumps and fans. Control of the flowrate is commonly achieved using valves, dampers and vanes to throttle the flow. However, these devices are inefficient as they normally result in an increased pressure drop across the system. An alternative and more efficient approach is to employ an electric motor fitted with a variable speed drive (VSD), alternatively known as an adjustable speed drive (ASD). Thus, a reduced flow is achieved by reducing the motor speed; there is no corresponding increase in the pressure drop. Given that the mechanical power requirement is approximately proportional to the cube of the fluid flowrate, it follows, for example, that in order to move 80 % of the flow, only half the power is required (Smith et al. 2007). Since the motor speed is very nearly proportional to the frequency of the input AC, the use of a variable-frequency supply is an effective and commonly used means of electronic motor speed control. A number of different techniques, also described by (Smith et al. 2007), are employed to generate this supply.

As part of its Best Practice Programme, the UK's Energy Efficiency Office investigated the benefits that could be achieved by replacing conventional electric motors with those fitted with a variable speed drive. Their results are summarized in Table 17.1. As may be seen, useful savings

Table 17.1 Summary of ETSU case studies on savings that can be achieved through the use of variable speed electric motors in the food industry [adapted from ETSU (1989); ETSU (1990); ETSU (1992)]

Case study no. (year)	Application	Capital investment	Annual savings, £	Payback time	Additional benefits
124 (1989)	VSDs on 75 kW secondary refrigeration pumps in a brewery	£11,500 (1989 prices)	227.4 MWh/year worth £7,958/year (1991 prices)	1.45 years	No noticeable change in maintenance requirements
126 (1990)	VSDs on 15 kW vacuum fan motors fitted to two bread depanners in a commercial bakery	£7,200 (1990 prices)	134,700 kWh/year, worth £5,500/year (1990 prices)	1.3 years	Reduced wastage, less maintenance
164 (1992)	VSD on 75 kW extract fan in a flour mill	£12,900 (1992 prices)	114,342 kWh/year worth £4,900/year (1990 prices)	2.6 years at 93 % of full speed or 1 year at 80 % of full speed	No noticeable change in maintenance requirements

were achieved in all cases, with paybacks ranging from typically 1 to 2 years. Flow control was originally achieved using valves in Case 124 (ETSU 1989) and dampers in Case 164 (ETSU 1992). In Case 126 (ETSU 1990), there was no control on the vacuum fans, which were always run at full speed. In this case, fitting motors with a VSD introduced an element of control that not only saved energy by cutting back on the fan speed in appropriate cases but also reduced product damage and hence wastage.

Although lighting typically accounts for a much lower electricity use than motors, its energy consumption is still significant. As discussed in Chap. 13, fluorescent light fittings, suspended beneath the ceiling or recessed in the ceiling with a flush diffuser, are commonly employed in food factories. These are reasonably efficient in terms of energy consumption compared with standard incandescent lighting. For further details of these and other lighting systems, see Atkinson et al. (2007).

Petchers (2007) described the different components that contribute to a typical industrial electricity bill. A thorough understanding of these components is necessary in order to minimize power costs. The simplest measure of the cost of energy (i.e., total annual cost divided by total kWh consumed) can be both misleading and inaccurate. It is important to note that each utility company will have its own charging structure, which should be considered when evaluating competing suppliers.

A typical electricity bill will consist of the following elements:

1. A monthly service charge.
2. A charge for the energy consumed.
3. A demand charge.
4. A power factor penalty.
5. Adjustments imposed by various regulatory authorities.
6. Fuel cost adjustments.
7. Taxes.

The effect of these, which may vary considerably between suppliers, is best evaluated using a spreadsheet. The monthly service charge (1) is a fixed payment that does not depend on the consumption or demand. The energy consumption charge (2) represents the cost of the kWh of electricity consumed during the billing period. Rates vary according to whether the electricity is consumed during the peak period (e.g., 10 a.m.–6 p.m. Monday–Friday), shoulder period (e.g., 6–10 a.m. and 6–10 p.m. Monday–Friday), or the off-peak period (e.g., 10 p.m.–6 a.m. Monday–Friday, all day Saturday and Sunday). Enhanced rates may also apply during the four summer months, June to September. The purpose of these differential rates is to shift consumption from periods of high to low demand. The demand charge (3) is normally based on the maximum power consumed (kW) in any one month during the previous 12. On occasions, this may exceed the consumption charge. The power factor penalty (4) has been discussed above and is normally charged if the power factor is below a stipulated value in the range 0.90–0.95. The imposed adjustments (5) may include, for example, a nuclear decommissioning charge. The fuel cost adjustment (6), which may be either positive or negative, is used to reconcile the latest cost of the fuel used by the utility to generate the electricity with that estimated at the most recent rate-setting proceedings. Finally, item (7) will include all taxes levied by national, state and municipal governments.

An estimation of possible energy consumption patterns and an understanding of the breakdown of the associated charges for electricity (and other utilities) may, if taken into consideration at the factory design stage, result in lower overall operating costs. For example, provision should be made to ensure that the start-up of electric motors, etc., within the factory is phased so that the associated initial power surge is spread over a period of time and hence that the maximum demand is reduced. This will result in a reduction in charge (3) above.

Zehr (1997) studied the operation of two cheese plants located at Marshfield and Blair in Wisconsin with a view to exploring how energy consumption and/or production costs could be reduced. The Marshfield plant consumes 730,000 kg/day of raw milk to produce around 71,000 kg/day of cheese (mostly cheddar and some mozzarella). There are two cold storage facilities capable of holding up to 1.6 million kg of cheese at 3.5 °C. At Blair, one million kg/day of raw milk are processed to yield 100,000 kg/day of cheddar cheese. Although this site also employs cold-storage facilities, they were not investigated. At both plants, whey powder is produced by evaporation and spray drying of liquid whey produced during the cheese-making process. Zehr identified three areas in which savings could potentially be made: evaporation (see Sect. 17.2.3) and spray drying (see Sect. 17.2.4) of whey and cold storage of the cheese.

The principal thermal load on the Marshfield cold store, which was unavoidable, was the heat that had to be removed in cooling 71,000 kg/day of warm cheese from its production temperature of 36 °C to its storage temperature (<4.5 °C) over a 7-day period. The then current practice was for the cooling system to be operated continuously. As an alternative, Zehr (1997) proposed the adoption of either full or partial thermal storage, which involved subcooling the bulk cheese in the cold store. With full storage, the total cooling load can be met by operating the cooling system only during off-peak hours. During peak hours, cooling of the warm cheese entering the cold store is achieved by allowing the temperature of the subcooled cheese to rise to its normal storage temperature. Full storage is possible when the degree of subcooling is acceptable. In the present case, for example, the cheese cannot be allowed to freeze. Partial storage, on the other hand, involves operating the cooling system under reduced load during peak hours. Neither approach would save energy but would reduce costs by demand shifting.

Zehr formulated a mathematical model of the cold store, which predicted that the full storage approach would not result in a swing of more than 2 °C in the bulk cheese temperature when 450,000 kg or more is kept in storage. This is acceptable. The calculated savings in electricity charges are shown in Table 17.2.

Zehr (1997) also investigated operating the cold store in “economizer” mode during the winter months when the outdoor temperature is less than the set point temperature. This involves ventilating the store with outdoor air, thereby allowing the cooling system to remain idle. Under these conditions, the only energy cost is that associated with running the ventilation fans. The additional savings resulting from this approach are also shown in Table 17.2. As may be seen, when taken together, the two cost-saving measures result in electricity cost savings of $15,718, which represents

Table 17.2 Predicted electricity cost savings in a cheddar cheese cold store in Wisconsin [adapted from Zehr (1997)]

Option	Annual energy cost, $	Saving, $	Saving, %
No storage, no economizer	19,362	–	–
Full storage	4,612	14,750	76.1
Economizer	–	4,339	22.4
Full storage + economizer	3,644	15,718	81.1

more than 80 % of the energy costs associated with operating the cold store. Moreover, very little additional capital is required to achieve these savings.

17.2.2 Cogeneration of Electricity and Thermal Energy

A knowledge of the electrical consumption pattern and billing structure will also enable the factory design team to assess whether cogeneration (or combined heat and power, CHP) is an economically viable proposition. This should always be considered in food factories in which sizeable quantities of both power and steam/hot water are consumed. Cogeneration is an energy- (and carbon-) efficient use of fuel, which is recognized in both the USA and the EU as an important element in developing a low-carbon economy. The thermal efficiency of a conventional power plant is, at best, 55 %; in contrast, that of a CHP plant can be as high as 89 % as a result of the recovery and utilization of waste heat that would be lost in a conventional power plant (Wikipedia 2010).

According to Fantozzi et al. (2000), a cogeneration plant is technically viable when the following four conditions are met:

1. There is a suitable balance between the electrical and thermal loads.
2. There is a simultaneous demand for both electricity and heat.
3. There is a demand for low-temperature heat.
4. The CHP plant is sited in close proximity to the user of the electricity and, in particular, the thermal energy.

There are three basic designs of cogeneration system. These are based on an internal combustion engine (ICE), a gas turbine (GT) and a steam turbine (ST). ICE-based systems are suitable for power outputs ranging from 10 kW to 10 MW. The electric efficiency, namely, the percentage of the heat content of the fuel that is converted into electricity, ranges from 30 to 40 % and the total efficiency (electric plus thermal) from 80 to 90 %. Thermal energy is produced at about 400 °C (from the exhaust gases) as steam or superheated water, and at about 90 °C (hot water) from the engine jacket, lubricating oil and aftercooler cooling systems. Gas turbines are suitable for power outputs in the range 2–200 MW with electric efficiencies in the range 15–40 %. Given that the heat is largely recovered from the exhaust gases, it will only be available at high temperatures (e.g., 500 °C). Finally, steam turbines are used for larger installations (>10 MW with electric efficiencies in the range 20–40 %). Heat can be removed either at high or low temperatures.

Several case studies of the application of cogeneration in the food industry have been published in the literature. Calderan et al. (1992) investigated the feasibility of installing a cogeneration unit in a slaughterhouse near Cesena, Italy that processed a total of 5×10^7 kg/year of chickens, turkeys, and quail. The production is distributed approximately uniformly over the year. Before installing the CHP unit, the base electrical load of the factory was 0.8 MW; the demand varied widely throughout the day and peaked during the early afternoon at around 1.7 MW in January to 2.7 MW in August. Electricity was purchased from the national utility. A significant fraction of this load (1.2 MW maximum) was utilized to power the 12 cold-store refrigeration compressors. Additional electric

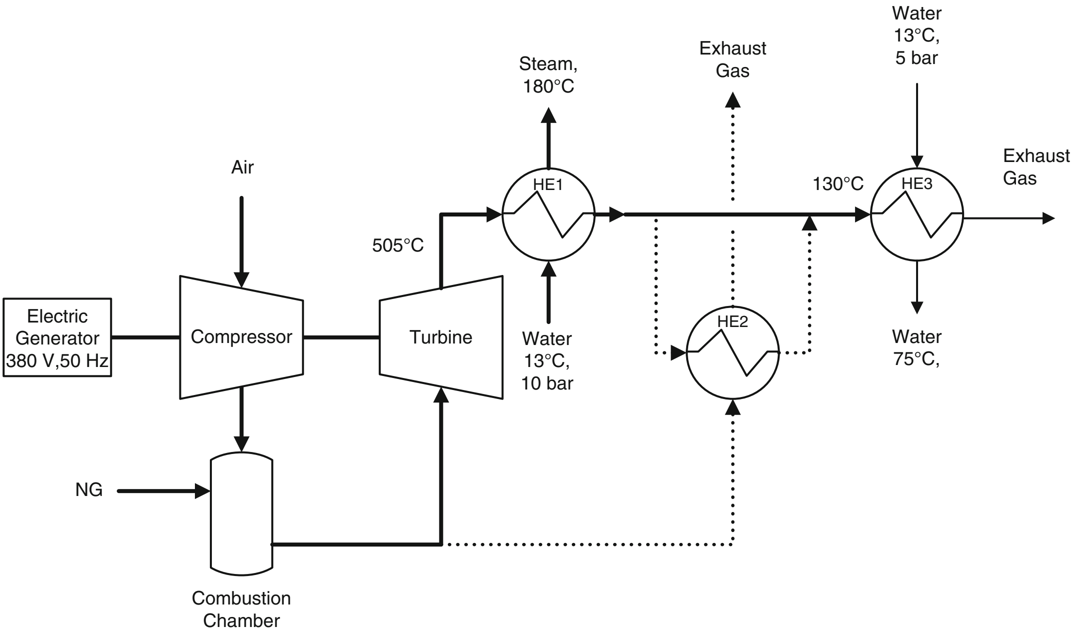


Fig. 17.1 Schematic illustrations of gas turbine cogeneration plant [adapted from Calderan et al. (1992)]

loads included four air compressors (0.2 MW), sundry machinery, pumps and lighting. Thermal energy was required to meet process needs. This included both 180 °C saturated steam (1.6×10^7 kg/year), produced in three natural gas steam generators, and hot water at 75 °C and 5 bar (4.8×10^7 kg/year) produced in waste-heat recovery units. The annual energy consumption of the factory was 9.7 GWh of electricity and 1.3×10^6 m^3 of natural gas.

Calderan et al. (1992) proposed the installation of a gas turbine cogeneration unit that would produce 0.755 MW of electrical power and 2.182 MW of thermal power. The equipment is shown schematically in Fig. 17.1. It consisted of a combustion chamber in which natural gas is burnt in excess air. The products of combustion are fed to a turbine, which drives both the air compressor and an A.C. generator. The gases leaving the turbine at 505 °C are used to generate steam in a waste heat boiler HE1 from which they normally leave at around 130 °C. These, in turn are cooled further in HE3 to produce hot water. Combustion gases can, if necessary, be employed in HE2 to adjust the inlet temperature to HE3. Calderan et al. (1992) described a computer simulation of the system from which they concluded that its introduction would reduce the annual electricity consumption from 9.7 to 4.3 GWh at the expense of increasing the natural gas consumption from 1.3×10^6 to 2.3×10^6 m^3/year. The authors claimed that this would result in annual savings of about $150,000 and a payback time of less than 5 years.

Fantozzi et al. (2000) conducted a detailed technical and economic study of the feasibility of installing CHP in an Italian agro-food factory. This consisted of three principal production units, namely, a wheat mill, an animal feed plant and a pasta plant. The electrical and thermal energy requirements for these plants (before installation of the cogeneration unit) are summarized in Table 17.3. The mill grinds wheat into flour. The soft-wheat flour is packaged and sold on the open markets, while the hard-wheat flour serves as feed to the pasta plant. The mill byproducts are sent to the animal feed plant. Only electrical energy, which is used to power the roller mills, separators, and fans, is employed in the mill. The animal feed plant produces a variety of products based on seeds (cereals and legumes), meal (e.g., from oil extraction), and liquids (molasses, fats,

Table 17.3 Electrical and thermal energy consumption in an agro-food factory [adapted from Fantozzi et al. (2000)]

	Electrical		Thermal	
Plant	Energy (MWh/month)	Power (kW)	Energy (MWh/month)	Power (kW)
Wheat mill	416	750 (± <10 %)	Nil	Nil
Animal feed	762	1,300 (±12 %)	63[a] 587[b]	106[a] 976[b]
Pasta	483	800 (± <10 %)	1,381[c]	2,246[c]

[a]Hot water (80 °C)
[b]Saturated steam (12 bar)
[c]Superheated water (120 °C, 5 bar)

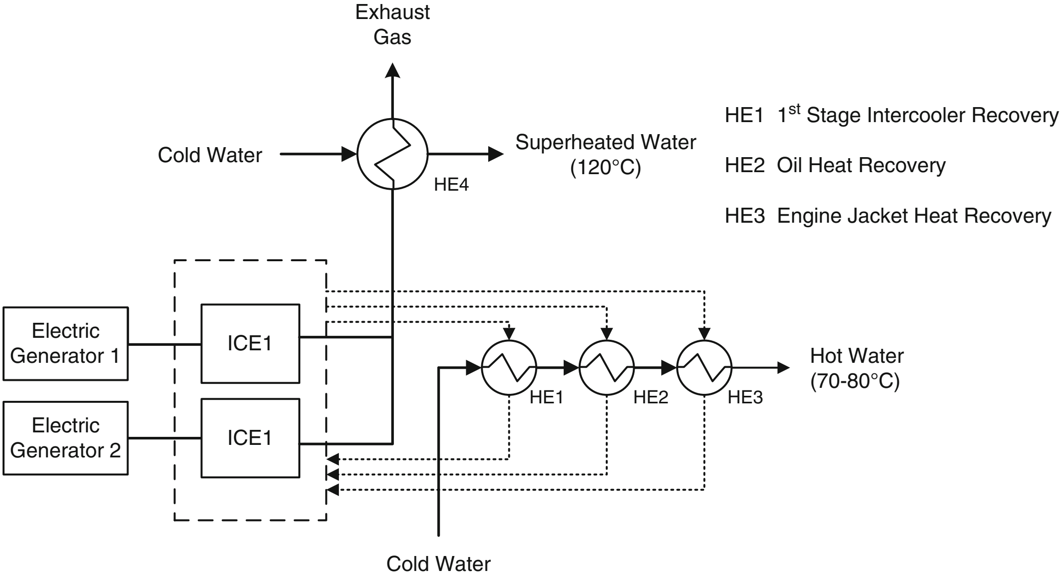


Fig. 17.2 Schematic illustration of a cogeneration unit driven by twin natural-gas fuelled internal combustion engines [adapted from Fantozzi et al. (2000)]

choline, and beet protein concentrate). The plant uses both electrical and thermal energy. The pelletizer accounts for over 75 % of the electrical energy consumption. Thermal energy is supplied both as 12-bar steam, which is used for cooking cereals, heating liquids and in the pelletizing operations. Hot water (80 °C) is used for heating the molasses. Finally, the pasta plant produces short pasta (macaroni, penne, etc.), long pasta (spaghetti, fettuccine, etc.), and nested pasta (tagliolini). Electricity is required to run a variety of mechanical devices in the plant, e.g., dough mixers, extruders, cutters, packaging machines, etc. The pasta dryers are heated by hot air warmed by 120 °C superheated water.

On the basis of the figures presented in Table 17.3, Fantozzi et al. (2000) concluded that a CHP system having an electric output of around 3,000 kW and an electric efficiency of around 40 % would be appropriate. Note that their choice is based on the electrical demand rather than the thermal load. As a result, they evaluated several cogeneration systems based on the internal combustion engine (ICE) and a gas turbine (GT). The latter option was eliminated on economic grounds. ICE-based systems (Fig. 17.2) typically recover 50 % of the thermal output at high temperature (450–500 °C) from the exhaust gases and 50 % at low temperature (90–120 °C) from the jacket, and lubricating oil and aftercooler cooling systems. Under these conditions it is not possible to recover all the heat

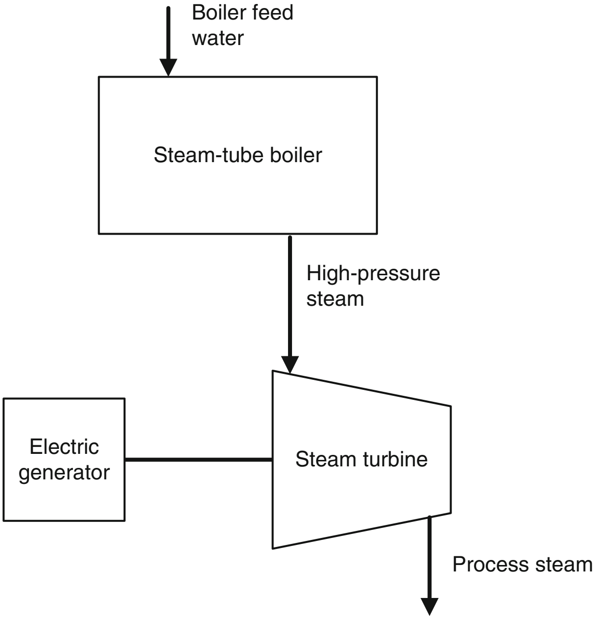


Fig. 17.3 Schematic illustration of a cogeneration unit driven by a steam turbine

required for production of the superheated (SH) water. The authors therefore proposed two options: (a) partial production of the SH water using the exhaust gases; (b) complete production of the saturated steam required for the animal feed plant using the exhaust gases. In both cases, the low-temperature heat recovered is used for office heating and the shortfall in the thermal load continued to be supplied using the existing facilities. Option (a) was found to the most economical. Two cases were considered. The first was based on one ICE delivering the total power required. This yielded an internal rate of return (IRR) of 20–26 % and a payback time of <4 years. The preferred choice, however, was based on two ICEs of half the power. In this case, the IRR was 24–29 % and the payback time <3.5 years.

Finally, Tiangco et al. (2005) published a pre-feasibility report on the installation of a cogeneration unit in a food factory in the Philippines. The principal product produced in this factory was a white crystalline umami seasoning powder manufactured mainly from sugar cane; no technical details of the process were given apart from the fact that it involved the usage of both heat and power. The former was produced using 10-year old boilers fired by bunker fuel oil (BFO) and the latter was purchased from the national grid. In the project described in the report, it was proposed to replace the existing boilers by a cogeneration unit designed for thermal load matching, which would produce the peak requirement of 50 t/h of 120 psi process steam together with 6,500 kW, which constituted the bulk of the power requirement. However, on average, 400 kW would still have to be supplied by the grid. The plant operates 24 h per day and 345 days per year, which is well suited to economic CHP operation.

The cogeneration system proposed in the Tiangco et al. (2005) report comprised a high-pressure, BFO-fired water-tube boiler and a steam turbine generator (Fig. 17.3). The capital cost of PhP 310 m (approximately US$7 million) included the purchase cost of the equipment and its installation and the construction of a new powerhouse. Their detailed economic analysis yielded a payback time of less than 2 years and very acceptable internal rates of return. Moreover, installation of the cogeneration unit resulted in significant environmental benefits, namely, a net emission reduction of more than 76,000 t CO_2e per year.

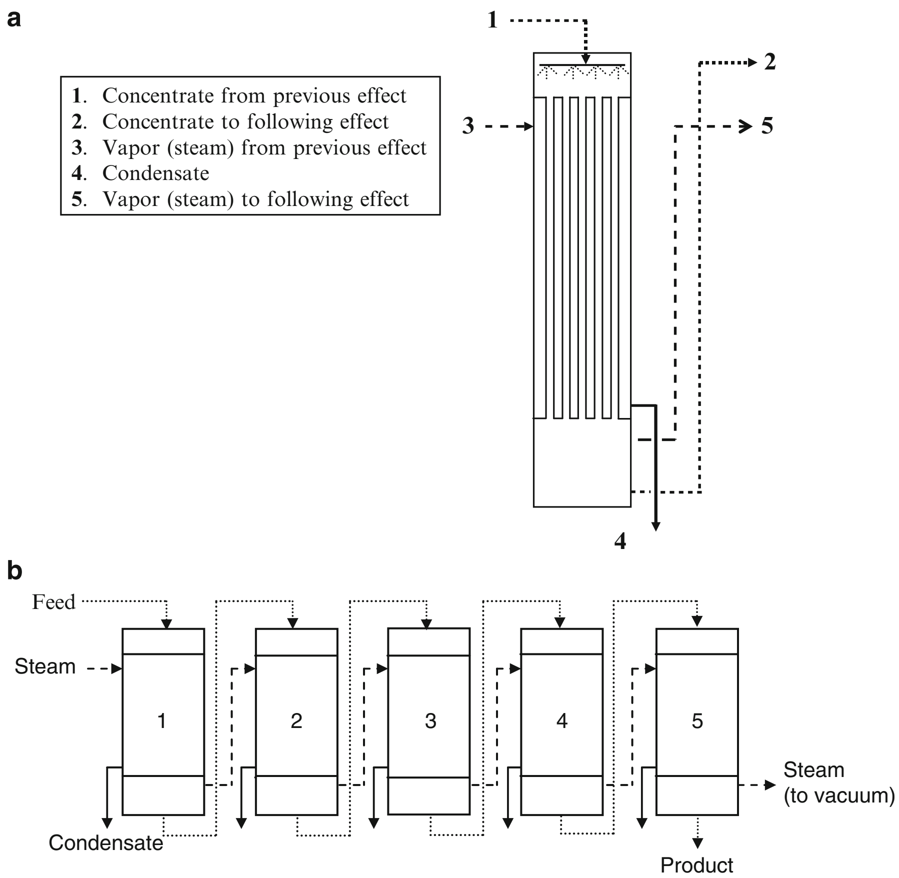


Fig. 17.4 Typical falling-film evaporators. (**a**) Schematic diagram of a single effect falling-film evaporator. (**b**) Schematic diagram of a 5-effect evaporator

17.2.3 Steam and Hot Water

Steam is widely used in the food industry for process- and space heating. Examples of the former include pasteurization, cooking, retorting, drying and evaporation, etc. Chapter 14 describes steam generation and use including various measures to maximize efficiency (e.g., effective steam trapping and condensate return).

Evaporators are major users of energy, which is normally supplied by condensing steam. Falling-film evaporators (Fig. 17.4) are widely used in the food industry as they are well suited to handling relatively low viscosity liquids that require short residence times in order to minimize thermal damage to the product. Three techniques employed to reduce energy consumption are considered here: multi-effect evaporation, vapor recompression, and heat recovery.

Most evaporation systems employ multiple effects (evaporator bodies in series). A typical effect in a falling-film evaporator is illustrated schematically in Fig. 17.4a. It is similar in construction to a vertically mounted shell and tube heat exchanger. The feedstock being evaporated flows downwards under gravity through the vertical tubes; steam condenses on the outside of these tubes and provides the necessary latent heat of vaporization. The concentrated feedstock is separated from the vapor formed inside the tubes and pumped out of the effect. In an ideal single-effect evaporator in which sensible heating and heat losses can be neglected, 1 kg of steam will evaporate 1 kg of water.

However, if the concentrate from the first effect is pumped to a second effect and heated by the vapor formed in the first effect, 1 kg of steam will ideally evaporate 2 kg of water, and so on. Thus, in an ideal N-effect evaporator, the economy (kg water evaporated per kg steam consumed) is equal to N. In practice, even though the economy of real N-effect evaporators is invariably less than N, very useful energy savings can still be achieved. There is an economic balance to be struck between an increased number of effects (higher capital costs) and the resulting lower steam costs. Figure 17.4b illustrates a typical five-effect evaporator. Note that the final effect is operated under vacuum and the pressure and temperature fall progressively between the first and the final effects.

A complementary approach to reducing the energy consumption of an evaporator is vapor recompression, which involves substituting all or part of the fresh steam supplied to the first effect with upgraded vapor generated in one of the intermediate effects. Two systems are commonly employed: mechanical vapor recompression (MVR) using a centrifugal compressor and thermal vapor recompression (TVR) using a steam jet ejector. Note that, as current technology permits a maximum temperature rise of around 16 °C during recompression, it is not normally possible to employ the vapor produced in the final effect since the temperature drop across the evaporator generally exceeds this value.

Process integration, also known as pinch technology or pinch analysis, is a widely used technique which is employed to calculate thermodynamically feasible energy targets that minimize process heating and cooling requirements and the pinch temperature across which heat should not be transferred (Wikipedia 2011). Thus, process integration facilitates the design of two optimum heat exchange networks, one operating above the pinch temperature and another below it. For a full description of the methodology, see for example Kemp (2006). Note that any heat recovery schemes identified through process integration must be analyzed to ensure that they are both technically and economically viable.

In his study of the cheddar cheese plant at Marshfield, Wisconsin (see Sect. 17.2.1), Zehr (1997) employed process integration to explore possible heat recovery schemes. He examined a number of options and concluded that significant savings could be achieved by recovering the heat released on condensing the 41 °C vapor generated in the final effect of the evaporator. He identified two appropriate heat sinks: (1) raw milk that will be preheated from around 5.5 to 35.5 °C prior to pasteurization, and (2) city water that will be heated from around 13 to 35.5 °C and stored for off-production cleaning. It was estimated that these two scheme would together reduce the boiler load by around 26.3 MWh per operating day, equivalent to annual savings of $72,800 (in 1997). Additional savings of around $3,000 would also be realized by eliminating the need for a cooling tower.

Analyses such as the above should always be carried out at the factory design stage in order to realize possible energy savings at the earliest opportunity and to avoid the unnecessary additional costs of retrofits, which may not be economical.

17.2.4 Natural Gas

Natural gas is widely used in the food industry as it is a clean, efficient fuel, which comprises essentially of methane (CH_4). When burnt, it produces 30 % less carbon dioxide, the principal greenhouse gas, than its main competitor, fuel oil. Acid gas (NO_x and SO_2) emissions are also significantly lower and particulate production is minimal. Petchers (2007) gives one example of a typical natural gas tariff structure, which is much simpler than its electricity equivalent. The invoice comprised a relatively small fixed service charge, a charge for the gas consumed, and taxes. The gas was priced on a sliding scale; the greater the consumption, the lower the unit charge. The minimum monthly charge (zero gas consumption) consists of the service charge plus taxes. The gas tariff does, however, depend on whether or not the supply is interruptible or non-interruptible (the latter, naturally, is subject to a higher charge).

Table 17.4 Capital-intensive schemes for reducing the energy consumption of dryers

Scheme no.	Description	Possible energy savings	Drawbacks
1	Recovery of heat from the exhaust air	17–40 %	Fouling of the heat exchangers and, to a lesser extent, corrosion. These can be overcome by employing glass heat exchangers fitted with clean-in-place washing systems
2	Partial recirculation of the exhaust air	Up to 20 %	Useful savings may not be possible with food products as relatively high exhaust air temperatures (e.g., 120 °C) are required
3	Utilizing waste process heat	Up to 100 %	The supply must be consistent, reliable, and compatible with the product. It may be appropriate to install a backup energy supply
4	Monitoring and advanced control	0–50 %, plus associated benefits of 0.5–1 times the direct energy savings.	None
5	Switching from an indirect to a direct heater	Up to 30 % on a primary fuel basis	Product must be compatible with the combustion gases
6	Prior dewatering of the dryer feedstock	Variable, depending on application	Method chosen must be compatible with process stream—e.g., evaporator with liquids and appropriate mechanical dewatering devices with solids

Dryers and baking ovens are major consumers of natural gas in the food manufacturing industry. Because of its clean-burning characteristics, natural gas is often the preferred fuel; however, steam and oil are frequently used alternatives. Over the working life of a typical convective dryer, the cost of fuel consumed is likely to be around five times the capital cost of the dryer (Gilmour et al. 1998). Consideration should always be given to installing heat recovery equipment and employing other measures to minimize the energy consumption at the outset as retrofits rarely prove economical because of the cost of the associated plant modifications that are required. Baker (2005) discussed a number of capital-intensive schemes for reducing the energy consumption of dryers. These are summarized in Table 17.4. The application of pinch analysis in the heat recovery from dryers has been discussed by Kemp (2005). As these two authors point out, heat recovery from dryers is often problematical as the energy savings achieved in practice are often significantly lower than predicted as a result of technical problems, e.g., fouling of heat exchanger surfaces due to the humid, dusty nature of many dryer exhausts. Care should therefore be taken when applying these methods.

It should also be born in mind that contact dryers (i.e., those in which the solids are heated by conduction from a hot surface) are inherently more efficient than convectively heated dryers. The use of heat pump and solar dryers may also be appropriate under the right circumstances. The selection of dryers for food products has been discussed by Baker (1997), Baker and Lababidi (2000, 2001), Baker et al. (2004) and Lababidi and Baker (2003).

Zehr (1997) also estimated the energy and cost savings that might be achieved through heat recovery from the 22 ft diameter by 30 ft tall spray dryer at Blair, Wisconsin. This, in combination with a vibrating bed dryer, is used to dry 5,455 kg/h of whey concentrate produced in the five-effect falling film evaporator discussed in Sect. 17.2.3 above. He explored a number of integration options including heat exchange between the inlet and exhaust air streams and partial exhaust air recirculation but opted for the former. The estimated annual cost savings ranged from $42,000 to $69,000 depending on the size of the heat exchangers employed. However, as noted above, further exploration of possible technical difficulties should be undertaken prior to adopting this approach.

Baking ovens can also be useful sources of reusable heat. Henderson et al. (2001), for example, described and measured the performance of a direct-contact heat recovery system that was installed in a commercial bakery in Brooklyn, NY. The flue gas from the oven was diverted to the bottom of a heat recovery stack. Water was sprayed into the top of a packed column and absorbed heat from the rising gases. It was then collected at the bottom of the column and pumped to a plate-and-frame heat exchanger in which it preheated either makeup air supplied to the oven or feed water to the boilers. In a 1-year study, the authors identified a number of technical problems, for example corrosion of the spray nozzles and instrumentation/control problems. The authors also noted that the annual value of the recovered heat was lower than anticipated because of faulty economic assumptions made at the outset. LeCompte (2008) described a German system used to recover heat from baking ovens. The flue gas and the steam generated in the baking process were treated separately; however, no details were given. The system was recommended for use in bakeries with more than four ovens and a gross burner capacity of over 320 kW.

17.2.5 Fuel Oil

The prime use of fuel oil in the food industry is to fire boilers and dryers. It is used extensively as a backup fuel for use in emergencies, particularly when the natural gas supply is interruptible (Woodruff et al. 2005). See Chap. 14 for further details on fuel oil.

17.3 Water

Water is used extensively in food manufacture for a variety of purposes. In the past, it was considered as a cheap and abundantly available commodity and little consideration was given to minimizing its use. However, in today's economic and industrial climate, water supply and treatment are considerably more expensive than in the past and its use must be considered both at the factory design stage and in subsequent manufacturing operations. Two chapters in this handbook address various aspects of water use: Chap. 14 discusses water treatment in relation to boilers and Chap. 18 wastewater treatment. Klemeš et al. (2008) focus in great detail on water use in food processing and the reader is referred to this work for a detailed analysis of this subject. In consequence, only a few topics that are particularly pertinent to food factory design are discussed here. The principal objective is to highlight design techniques that minimize raw water usage and wastewater generation.

Water has many uses in food processing. Pagan and Price (2008), for example, cited the data shown in Table 17.5 for different food products. As may be seen, these vary quite widely. Water addition to the product (e.g., soft drinks, colas, reconstituted fruit juices, etc.) is self-evident. This naturally needs to be of potable quality. Cleaning operations often consume large quantities of water and generate equally large quantities of wastewater. In order to facilitate effective cleaning regimes, the factory infrastructure, particularly the floors and drains, and process equipment should be designed in

Table 17.5 Typical water usage in different food industry subsectors [after Pagan and Price (2008)]

	Food industry subsector			
Water-consuming activity	Beverages (%)	Meat processing (%)	Vegetable processing (%)	Dairy products (%)
Water added to product	60	0	0	0
Cleaning operations	25	48	15	49
Cooling tower makeup	2	2	5	6
Processing operations	8	47	78	42
Auxiliary uses	5	3	2	3

accordance with the hygienic principles set out in Chaps. 13 and 4, respectively. Consideration should also be given to adopting cleaning methods that reduce the quantity of water consumed, e.g., the use of high-pressure cleaning rigs or dry-cleaning methods (Pagan and Price 2008).

Water is often used for cooling purposes. In such cases, closed loop systems are frequently employed in which the coolant is returned to a near ambient temperature in, for example, a mechanical draft cooling tower. In such loops, makeup water, which is required to compensate for losses, is the sum of the evaporation loss, the drift loss and the blow-down (Green and Perry 2008). Of these, the evaporation loss constitutes the major component. As this is proportional to the circulating water flowrate and the difference between its inlet and outlet temperatures, minimizing these parameters by good process design will reduce the water makeup requirements. In the example cited by Green and Perry (2008), the makeup constituted about 8 % of the circulating cooling-water flow.

Processing operations in food factories include heating and cooling, steam-raising, rinsing, conveying, washing, blanching, cooking, etc. Each of these should be designed in such a manner as to minimize water usage. Finally, auxiliary use includes water consumption not directly associated with the manufacturing process—e.g., laboratories, staff restaurants, toilets, etc.

Kim and Smith (2008) discussed several techniques for minimizing water usage in food-manufacturing facilities. Their methodology was similar to that employed in pinch analysis used to minimize energy consumption. The authors illustrated their approach by means of a simple example involving three operations with different water flow and quality requirements. In the present context, the term “quality” may denote the concentration of a soluble (or suspended) component that is transferred from the process stream to the water during each individual operation. If multiple components are involved, it is preferable to employ a composite measure such as BOD, COD, or total solids. In its simplest form, their graphical approach can be used to minimize the fresh water flow that satisfies all process requirements.

In practice, as Kim and Smith (2008) point out, practical water-minimization problems are considerably more complicated than the simple example presented in their article. The principal reasons for this are as follows:

1. Most food factories will involve a relatively large number of operations that utilize water. It is also possible that multiple water sources of different quality could be employed.
2. The water quality can be dictated by temperature as well as solids concentration.
3. Water networks may include the following design options to further reduce consumption.
   Water reuse: Water from one operation can be used in a second operation if the outlet quality from the first operation is acceptable for use in the second operation.
   Regeneration recycling: Water from a specific operation is sent to a water-treatment plant and is recycled to the same operation.
   Regeneration reuse: Water from a specific operation is sent to a water-treatment plant and reused in a different operation.
4. Food manufacture often involves batch processing. See Kim and Smith (2004) for techniques that can be used to handle such operations.
5. Calculations can be complicated by water losses (e.g., cooling tower and boiler blow-downs).

Designing and optimizing water supply and treatment facilities is therefore a complex task that is best handled by computers. Kim and Smith (2008) cite the three suitable programs listed in Table 17.6. Invariably, these will generate multiple options that will require further technical and economic screening to determine the optimum solution. Note that there may also be several equipment options having different water requirements that can service the needs of each operation. Each will have to be assessed. The authors cite two case studies taken from Klemeš and Perry (2007) to illustrate their use.

Table 17.6 Software for water minimization [after Kim and Smith (2008)]

Program	Vendor	Web site
WATER®	Centre for Process Integration, The University of Manchester	http://www.cpi.umist.ac.uk/consortium/RC_brochureWeb.pdf
Aspen Water®	Aspentech	www.aspentech.com
WaterTarget®	KBC Advanced Technologies	http://www.kbcat.com/

17.4 Conclusion

As is the case in all manufacturing operations, the efficient use of both energy and water is becoming increasingly important in food production. This chapter outlines techniques that can be employed to reduce the consumption of these important commodities. In particular, the use of cogeneration, where appropriate, energy-efficient motors, heat recovery, and minimization of water usage through reuse and recycling are important considerations.

References

Atkinson, B., Denver, A., McMahon, J.E. and Clear, R. (2007) “Energy-efficient lighting technologies and their application in commercial and residential sectors”, Section 12.2 in “Handbook of energy efficiency and renewable energy”, (ed.) Kreith, F. and Goswami, D. Y., CRC Press, Boca Raton, FL.

Baker, C.G.G. (1997) “Dryer Selection”, Chapter 10 in “Industrial drying of foods”, Baker, C.G.J. (ed.), Chapman & Hall, London.

Baker, C.G.J. and Lababidi, H.M.S. (2000) “Development of a fuzzy expert system for the selection of batch dryers for foodstuffs”, Drying Technology, 2000, 18, 117–141.

Baker, C.G.J. and Lababidi, H.M.S. (2001) “Developments in computer-aided dryer selection”, Drying Technology, 19, 1851–1873.

Baker, C.G.J., Lababidi, H.M.S. and Masters, K. (2004) “Fuzzy expert system for the selection of spray-drying equipment”, Drying Technology, 22, 237–258.

Baker, C.G.J. (2005) “Energy-efficient dryer operation – An update on developments”, Drying Technology, 23, 2071–2087.

Calderan, R., Spiga, M. and Vestrucci, P. (1992) “Energy modelling of a cogeneration system for a food industry”, Energy, 17(6), 609–616.

Capehart, B.L. (2007) (ed.) “Encyclopedia of energy engineering and technology”, Taylor and Francis, London, 1936 pp., http://www.tandfonline.com/doi/book/10.1081/E-EEE.

ETSU (1989) “Variable speed drives on secondary refrigeration pumps”, Energy Efficiency Best Practice Case Study 124, Energy Technology Support Unit, Harwell, Didcot, Oxfordshire OX11 0RA, UK.

ETSU (1990) “Variable speed drives in a bakery”, Energy Efficiency Best Practice Case Study 126, Energy Technology Support Unit, Harwell, Didcot, Oxfordshire OX11 0RA, UK.

ETSU (1992) “Variable speed drives on a flour mill”, Energy Efficiency Best Practice Case Study 164, Energy Technology Support Unit, Harwell, Didcot, Oxfordshire OX11 0RA, UK.

Fantozzi, F., Ferico, S.D. and Desideri, U. (2000) “Study of a cogeneration plant for agro-food industry”, Applied Thermal Engineering, 20, 993–1017.

Gilmour, J.E., Oliver, T.N., Jay, S. (1998) “Energy use for drying processes: The potential benefits of airless drying”, Proc. 11th International Drying Symposium, Halkidiki, Greece, August 19–22, 1998, Volume A, pp. 573–580.

Green, D.W. and Perry, R.H. (2008), (eds) “Perry’s chemical engineers’ handbook”, 8th edit., McGraw Hill, New York, pp. 12–20, 21.

Henderson, H.I., Jr., Ciolkosz, D.E., Guerrero, P.S. and Levy, D. (2001) “Measured performance of a direct-contact heat recovery system installed at a commercial bakery”, presented at ACEEE Summer Study on Energy Efficiency in Industry, Tarrytown, NY, August.

Kemp, I.C. (2005) “Reducing dryer energy use by process integration and pinch analysis”, Drying Technology, 23, 2089–2104.

Kemp, I.C. (2006) “Pinch analysis and process integration: A user guide on process integration for the efficient use of energy”, 2nd edit., Butterworth-Heinemann, Oxford, UK, 416 pp.

Kim, J.-K. and Smith, R. (2004) “Automated design of discontinuous water systems”, Process Safety and Environmental Protection, 82(B3), 238–248.

Kim, J.-K. and Smith, R. (2008) “Methods to minimize water use in food processing”, Chapter 5 in Klemeš, J., Smith, R. and Kim J.-K. (eds) “Handbook of water and energy management in food processing”, Woodhead, Cambridge, UK.

Klemeš, J., Smith, R. and Kim J.-K. (2008) (eds) “Handbook of water and energy management in food processing”, Woodhead, Cambridge, 1056 pp.

Klemeš, J. and Perry, S. (2007) “Process optimization to minimize water use in food processing”, in Waldron, K. (ed.) “Handbook of waste management and co-product recovery in food processing”, Volume 1, Woodhead, Cambridge, UK, 90–115.

Kreith, F. and Goswami, D. Y. (2007) (eds) “Handbook of energy efficiency and renewable energy”, CRC Press, Boca Raton, FL, 1560 pp.

Lababidi, H.M.S. and Baker, C.G.J. (2003) “Web-based expert system for food dryer selection”, Computers and Chemical Engineering, 27, 997–1009.

LeCompte, C. (2008) “German baking supplier cuts bakeries’ energy waste 25 percent”, http://earth2tech.com/2008/10/17/german-baking-supplier-cuts-bakeries-energy-waste-25-percent/, dated 17 October.

NFPA (2008) “National Electrical Code”, 2008 edit., National Fire Protection Association, http://www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=70&cookie_test=1.

Pagan, R. and Price, N. (2008) “Good housekeeping procedures to improve the efficiency of water use in food processing plants”, Chapter 11 in Klemeš, J., Smith, R. and Kim J.-K. (eds) “Handbook of water and energy management in food processing”, Woodhead, Cambridge, UK.

Petchers, N. (2007) “Utilities and energy suppliers. Bill analysis” in Capehart, B.L. (ed.) “Encyclopedia of energy engineering and technology”, Taylor and Francis, London, 1936 pp., http://www.tandfonline.com/doi/book/10.1081/E-EEE

Ramirez, C.A., Blok, K., Neeli, M. and Patel, M. (2006) “Adding apples and oranges: The monitoring of energy efficiency in the Dutch food industry”, Energy Policy, 34, 1720–1735.

Smith, C.B., Capehart, B.L. and Rohrer,W.M., Jr. (2007) “Industrial energy efficiency and energy management”, Section 14 in Kreith, F. and Goswami, D. Y. (eds) “Handbook of energy efficiency and renewable energy”, CRC Press, Boca Raton, FL.

Tiangco, C.C., Custodio, S.C. and Tongco, E.O. (2005) “Cogeneration in the food industry: A pre-feasibility report”, http://www.docstoc.com/docs/23548519/Cogeneration-in-the-Food-Processing-Industry.

Wikipedia (2011) “Pinch analysis”, http://en.wikipedia.org/wiki/Pinch_analysis.

Wikipedia (2010) “Cogeneration”, http://en.wikipedia.org/wiki/Cogeneration.

Woodruff, E.B., Lammers, H.B. and Lammers, T.F. (2005) “Steam plant operation”, 8th edit., McGraw Hill, New York, pp. 305–318.

Zehr, S. (1997) “Process energy efficiency improvement in Wisconsin cheese plants”, MSc Thesis, University of Wisconsin – Madison, http://www.minds.wisconsin.edu/handle/1793/7763.

Chapter 18
Effluent Treatment

W.E. Whitman

18.1 Preliminary Considerations

Effluent treatment will need to be considered in the course of the design of every food factory because water plays such an important part in the hygienic processing of foods. Almost invariably it will cost money to dispose of effluent; good design can minimize this cost. However, operating any but the simplest treatment plant will require management time and attention, and extensive treatment may require specialist skills.

Food-factory effluents are essentially a specialized form of domestic effluent. Nearly all the treatment techniques and equipment are based on designs, which also play a part in the treatment of municipal wastes. Treatment of both municipal and food-factory wastes can be separated into three phases:

- Primary (preliminary) separation of solids and matter that can be removed by physical means.
- Secondary treatment by biological means to break down organic matter, with removal of some coagulated sludge.
- Tertiary treatment to improve further the quality of the wastewater so that it meets the requirements for discharge into a watercourse.

Before any design can be attempted, it is necessary to make an estimate of the likely nature and magnitude of the effluent to be treated. In the case of an existing factory, the necessary figures can be collected by sampling and measurement within the factory. In the case of a new factory, this information may be available from other similar factories, from textbooks and other published sources, or from design data arising from the specification of the factory concerned. Over a period of years, the nature and quantity of production will change; some flexibility and expansion capacity is desirable in in-factory effluent-handling facilities as it can be difficult and expensive to make subsequent changes to civil engineering works such as drains and sumps.

Effluent discharge is always going to cost money, and it is a good practice to consider whether it is possible to reduce the volume of liquid to be discharged by more careful use of water or by recycling or reusing water. Cooling water from later stages of the process may for instance be reusable as flume waters or for preliminary washing. More importantly, it may be possible to recover useful and valuable organic components of the effluent as by-products—for example, lactose from milk factory wastes or protein from meat factories.

W.E. Whitman (✉)
Leatherhead Food Research, Leatherhead, Surrey KT 22 7RY, UK
e-mail: williamewhitman@aol.com

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_18,

Table 18.1 Specifications for an effluent treatment plant

The following questions are among the more important ones, which need to be answered in preparing a specification for an effluent treatment plant

1. Is the factory operation optimized with regard to waste reduction (volume and strength)?
2. Are strong wastes segregated?
3. What is the variation of flow and composition, hourly/daily/monthly?
4. Does the factory product mix vary throughout the year?
5. What forward predictions are available for requirements in 5/10 years?
6. What type of treatment is required? Primary only, secondary, or tertiary?
7. What discharge quality is required? Is this likely to change in the next 5 years?
8. Where is space available for a treatment plant? Local geology?
9. Are there special components in the effluent? Sterilants?
10. Are there factory factors affecting the choice of effluent plant?

Information that is required for the design of a treatment system will include:

- Volume of wastewater from each process, including its variation throughout the working day
- Fat in each process stream
- Solids content—dissolved and dispersed solids in each process stream
- Temperature and pH
- Volume of runoff water from factory buildings and yards and seasonal variations thereof
- Volume of foul water from staff amenity facilities

This will give an indication of the magnitude of the design problem. As a check, most food factories will discharge roughly 90 % of the water they take in. The most obvious exception is the manufacture of sugar from sugar beet, where a net surplus of water is discharged. Production profiles change in factories over the year and throughout the day, and any information collected should take account of these variations.

Other factors will dictate the design options. These include the following:

- Is there a local sewage works, which can receive and treat the putative effluent from the factory? When factories are to be built on green field sites, there may well be insufficient local sewage treatment capacity to receive the proposed discharge. It may nevertheless be better to discuss public authority treatment, which may perhaps require a contribution to the capital cost of the required extension, rather than to build one's own facility.
- Is the factory and product susceptible to the possible carry-over of aerosol-borne bacteria from any treatment plant operated on factory premises? Bacteria and aeration are important aspects of the full treatment of food effluents. There is thus a strong possibility of airborne bacteria being carried into the production areas unless the treatment plant is substantially downwind of and well screened from the factory.

Table 18.1 lists a number of the more important questions that need to be answered in preparing a specification for an effluent treatment plant.

Full on-site treatment of a factory effluent will require that its quality be raised to a level compatible with the water body, be it stream, canal, lake, estuary, or sea into which it is to be discharged. The standard required is set by the authority responsible for the quality of the receiving water. In most cases bacterial treatment will be required to reach this standard. Two consequences of this need to be considered. Firstly, there is a reasonable possibility of off-odors being produced from time to time. Flies and other insects could possibly be attracted as well. Secondly, antibacterial agents in the factory discharge can adversely affect the operation of the treatment process. Examples from the author's experience include chlorine solutions, orange oil, salt, diesel oil, and caustic soda solutions.

If the treatment plant is operated by the factory, then any variation in quality or quantity of the waste must be absorbed and accommodated by the treatment plant. All management responsibility rests on the factory. Any effluent treatment plant breakdown becomes a factory problem, and any mistake in the factory leading to a malfunction of the treatment plant, such as an oil spill, can immediately be traced. A failure of the treatment plant for any reason can lead to the organization responsible for receiving the treated waste refusing to take the effluent. This could lead to factory closure or to very expensive alternative measures having to be taken. It may be wise to seek insurance against this risk.

In the UK, effluent charges are calculated using the Mogden formula, which is based on the relative costs of different aspects of the sewage treatment operation. There are several variants of this formula, but typically, it may be written:

$$\text{Charge/m}^3 = R + V + V_{\text{b}+}(O_\text{t}/O_\text{s})B + (S_\text{t}/S_\text{s})S \tag{18.1}$$

Here, R is the charge for collecting and receiving the waste (£0.18/m^3).

V is the charge for pumping and primary treatment (£0.15/m^3).

V_b is an additional charge for pumping and primary treatment if there is no biological treatment (£0.07/m^3).

B is the charge related to biological (secondary) treatment (£0.22/m^3).

S is the charge related to the treatment and disposal of solid material (£0.32/m^3).

O_t/O_s and S_t/S_s are ratios, which relate the relative strength of the trade waste (t) received to the standard (s) waste treated in the works. For example, O_t/O_s can denote the ratio of the chemical oxygen demand (COD) of the trade effluent to that of the settled sludge and S_t/S_s the ratio of the solids content of the trade effluent to that of the settled sludge.

The values of the components of the formula (except O_t and S_t) are published by each treatment company and can be used to calculate the total charge for wastewater discharged from a factory and the potential value of any improvement made to the factory in terms of reduced costs of discharge. There are several websites on the Internet that provide spreadsheets that may be used for calculating water treatment costs using the Mogden formula. Oasis (2012) is particularly useful as it provides the values of R, V, V_b, B, and S for 11 UK water companies. Average values estimated from these figures are given in parentheses above. The charges levied by each company for treating 500 m^3 of wastewater having a COD of $O_\text{t} = 200$ mg/l and a solids content $S_\text{t} = 300$ mg/l were calculated assuming that O_s and S_s were both 1,000 mg/l. The charges ranged from £1,549 to £5,710 with an average of £2,852.

The cost of waste disposal is significantly greater than the cost of water purchase. It will often be found that the major component of the formula charge for receiving and treating a food-factory waste is the cost of biological treatment. The formula gives a cost/m^3 so diluting the effluent will increase the charge. It is thus very important to control costs by managing the use, recycling, and disposal of water and to reduce as far as possible the amount of "waste" material which is "washed down the drain." Any possibility of sweeping up, sucking up, or otherwise preventing this from happening should be taken. Water conservation is discussed in Sect. 17.3 of Chap. 17.

It is useful at all times to consider ways of reducing the volume of water and the weight of solids discharged as factory effluent. If this aspect of the operation has not been optimized, the effluent plant may be oversized and the running costs will be unnecessarily high. Checks of this aspect should be made at several points during the design exercise and should continue during the whole period of use of the factory.

Before a liquid waste may be discharged, it is necessary to secure agreement from the processing authority. The basis of this agreement is the "Consent"; this will stipulate the quality and quantity of waste that may be discharged. The parameters that are stipulated in a Consent may vary from sewage

Table 18.2 Typical parameters listed in a Consent

Parameter	Typical values/comments
Temperature	<43 °C (possibly lower)
pH	Range 6–10, to protect sewers and bacterial activity
Fat	<100 ppm (possibly lower)
Suspended solids	<500 ppm
Volumetric flow (24 h) Volumetric flow (1 h)	These two figures are to protect against unexpected expansion and short-term overloads at the treatment works

works to sewage works depending on the nature of the treatment facilities available, the size of the works, and the requirements set on the effluent treatment plant for the quality of its own discharge. Typical parameters are summarized in Table 18.2.

A "Consent to Discharge" is a contract. Any occasion when the permitted figures are exceeded is a breach of this contract. Repeated breaches could lead to the permission to discharge being withdrawn; this could result in closure of the factory.

18.2 Measurement and Sampling

There are a number of terms and measurements used in effluent treatment, which it may be helpful to outline. Appropriate national standard techniques should be used for these measurements.

18.2.1 Open Channel Flow

Effluents frequently flow in part-full drains or open culverts. Flow rates are therefore measured by recording the height of the flow above a weir of some sort. Weirs may be of varying geometry depending on the shape of the channel and the rate to be measured. It is essential that the weir notch is kept clean to ensure accuracy and it is desirable to monitor flow over a period of time to allow for its variability during the production cycle. A dirty weir tends to give too high a reading. Moreover, in order to achieve an accurate flow measurement, it is necessary to install adequate straight lengths of the drain or culvert upstream and downstream of the weir.

A flowmeter for use in open channels, which computes flow rates by measuring flow velocity with a magnetic flow sensor and level with an ultrasonic level transmitter, is now available. This obviates the need for a weir.

It is common practice for sewage treatment authorities to require factories discharging to their plant to maintain a recording flowmeter at the point of discharge of the factory waste. Samples for charging will be taken at this point, and the charge will be based on the aggregated flow multiplied by the measured quality parameters. These flowmeters are usually installed in a stilling well adjacent to the weir or flume. All this equipment should be kept clean.

18.2.2 Sampling

Samples should be representative of the flow. Automatic sampling allows samples to be taken at regular intervals; with some samplers, these can be flow proportional. A separate sample should always be taken for measuring fat content because, as the sample cools, fat will coagulate and rise and the whole of this second sample will be required to make a representative measurement.

18.2.3 Chemical Oxygen Demand

This is the commonly used measure of the organic matter in the wastewater. For all intents and purposes, it has completely replaced the older biological oxygen demand (BOD) because the test method gives greater reproducibility and is much quicker to perform. In this test, the waste is oxidized with a strong oxidizing agent (potassium dichromate) in an acidic medium, and the amount of chemical used up in the oxidation reactions is measured.

Some equipment manufacturers suggest total oxygen demand as an alternative as it can be measured in-line. To use this technique, it is necessary to establish an appropriate correlation for each individual factory.

18.2.4 Suspended Solids

This is the material in the effluent too small to be screened out but coarse enough to be filtered. It is measured by filtering the waste and drying and weighing the deposit.

18.2.5 pH

Traditional glass electrode pH meters are not very suitable for effluent work, as they are fragile and difficult to clean and standardize in the working environment. Ion-sensitive field effect transistors offer the possibility of a robust device suitable for food-factory and effluent use.

18.2.6 Dissolved Oxygen

This is a measure of the availability of oxygen in the wastewater. It is normally measured in-line by a special electrode and the signal may be used to control the degree of aeration of the liquor. If the waste becomes anaerobic, then sulfur-reducing bacteria will become active and produce foul-smelling and potentially dangerous gases. Excessive oxygenation is expensive and may lead to the growth of an excess of bulky sludge.

18.2.7 Sludge Volume Index

This is the volume in ml occupied by 1 g of activated sludge after settling for 30 min. A lower sludge volume index (SVI) is desirable; normal figures are in the range 70–100.

18.2.8 Mixed Liquor Suspended Solids

Mixed liquor suspended solids (MLSS) is the quantity in parts per million (ppm) of solids in the aeration vessel.

18.3 Primary Treatment

In this phase, all suitable means are used to remove as much as is practicable from the waste before it moves to the next treatment stage. Because primary treatment is mainly physical in character, it can beneficially be considered for use in every food factory. It may, in fact, be necessary to make use of some primary processes in order to bring the effluent up to the standard required by the "Consent to Discharge."

It is sensible at this stage to consider what separable material can get into the drain from each individual process in the factory. Firstly, it makes economic sense to reduce the amount of material entering the drains—it is usually considerably more expensive to treat a kilogram of organic material as liquid waste than as solid waste. Secondly, it is relatively easier to recover material from a simple discharge from one process. Recovery from a mixed discharge from a number of processes is frequently a much more complex process. This is why it is desirable to know the volume and composition of the discharges from every individual process in the factory. Figure 18.1, which relates to the slaughter and processing of broiler chickens, shows how, by knowing strengths and separating flows, half the organic matter in the waste can be concentrated into a quarter of the flow. A diagram of this form showing the likely characteristics of the wastewater from each process can be of great value to the designer. For example, the wastewater in the "feather and waste offal" flume will need to be screened to remove feathers and other solids. Such a screen in the immediate plant will be smaller and easier to manage than one designed to handle the combined flow.

Similar considerations apply to the trapping of fats, which are more easily separated if the wastewater is cool and not contaminated with proteins. Flumes at the point of origin are not as deep as those required when waste streams have been combined and have left the factory; it is thus

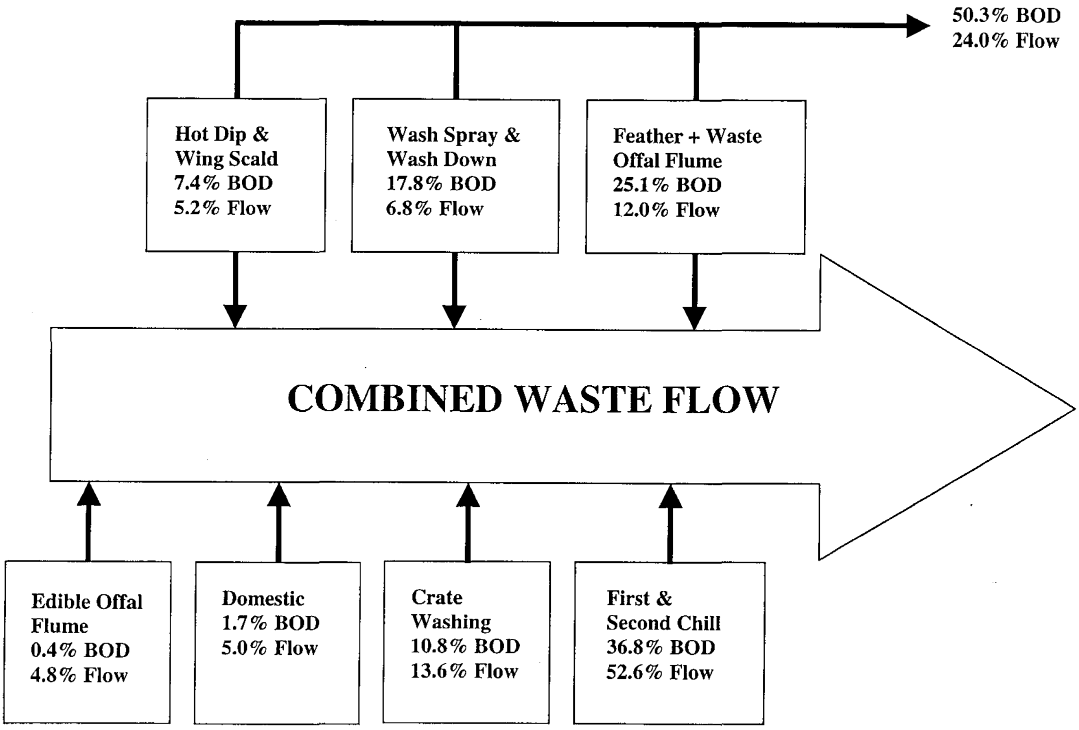


Fig. 18.1 Effluent streams from a broiler chicken processing plant

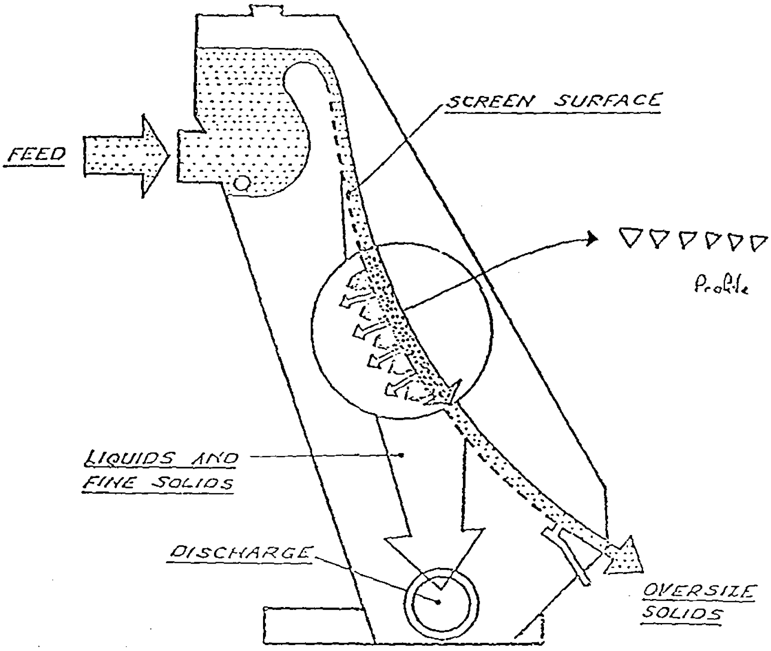


Fig. 18.2 Wedge-wire screen

easier and less expensive to install and manage suitable equipment. Some segregated wastewater flows may contain very little contamination. In such cases, they can be reused or used in another process, thereby reducing overall water demand and the volume of effluent to be treated.

There are three main groups of equipment, which may be suitable for primary treatment of food-factory wastes:

- Grids and screens for removing solids
- Flotation devices for removing fats
- Aeration equipment for removing proteins and fats

When selecting primary treatment equipment, it is necessary to consider the loss of head over each item of plant. Pumping is expensive and it may affect the separability of components of the waste.

18.3.1 Equipment for Primary Treatment

18.3.1.1 Grids and Screens

Many designs are available from manufacturers; it is always useful if a self-cleaning design can be selected. Wedge-wire screens (Fig. 18.2) are particularly useful where particles are long and thin and flows are high. Brush and rotary screens (Fig. 18.3) are lower in cost and are widely selected in the fruit and vegetable processing sectors. All screens should be protected by a coarse grid (Fig. 18.4) to take out large solids, which could cause damage. A grit removal device that traps small heavy solids so that they may be removed should also be considered, especially when processing field crops.

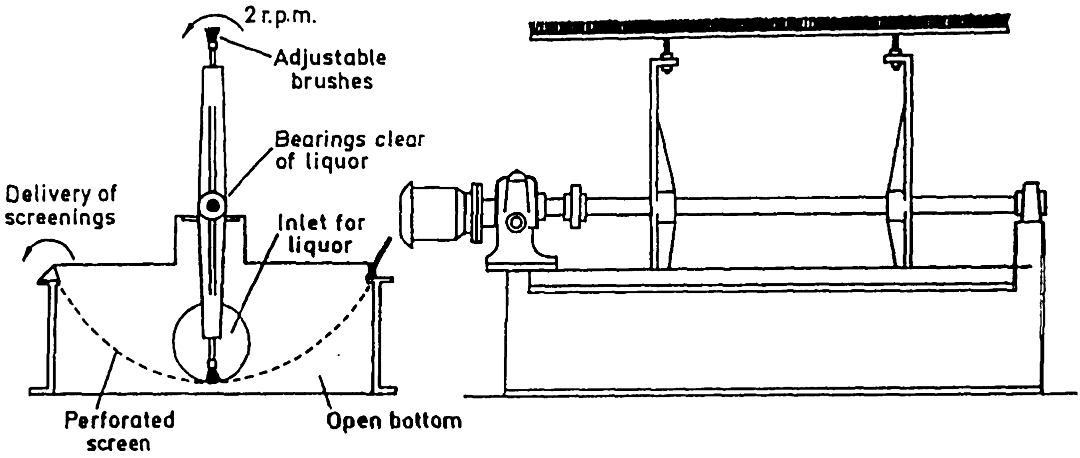
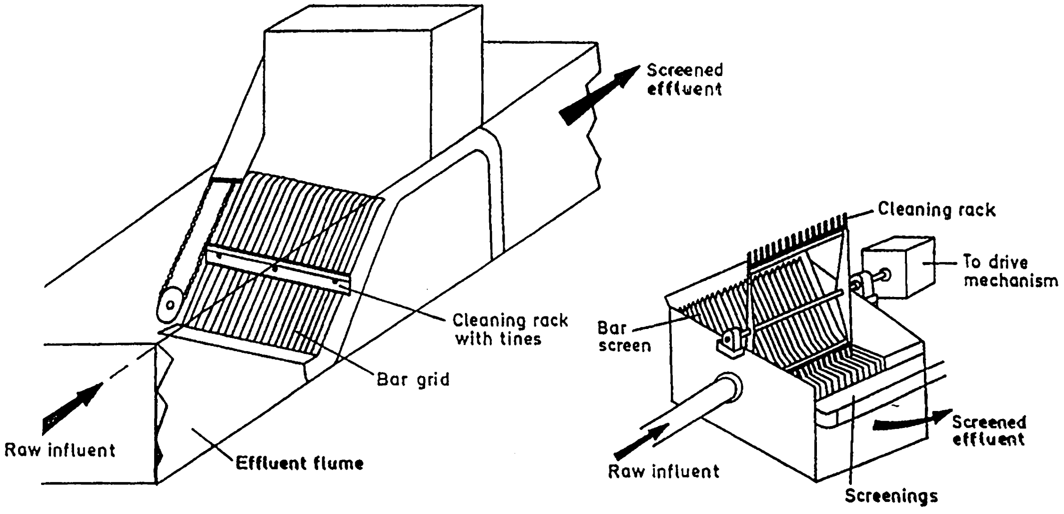


Fig. 18.3 Brush and rotary screen



Parallel flow *Side entry of flow*

Fig. 18.4 Screen protection grid

18.3.1.2 Fat Traps

Fat is lighter than water and will rise to the surface from which it may be skimmed off as long as it has not been emulsified by mixing with protein in hot water. This is an important argument for fat separation at the point of origin. Waste entering a fat trap should be neutral or acidic. Alkaline wastes emulsify more readily and excess alkalinity could lead to soap formation, which would dissolve some of the fat in the waste stream. For the same reason, detergents and cleaning solutions should be diverted from the trap system.

A fat trap (Fig. 18.5) should be designed to give a minimum 20-min residence time in a settler in which the flow is Newtonian. In order to increase the hydraulic diameter and slow the flow, it may be desirable to add vertical, longitudinal baffles, parallel to the direction of flow. On no account should

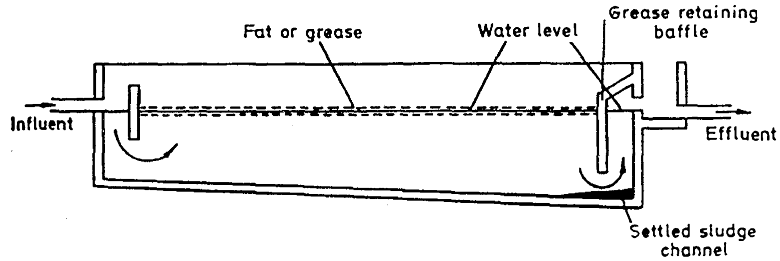


Fig. 18.5 Fat trap

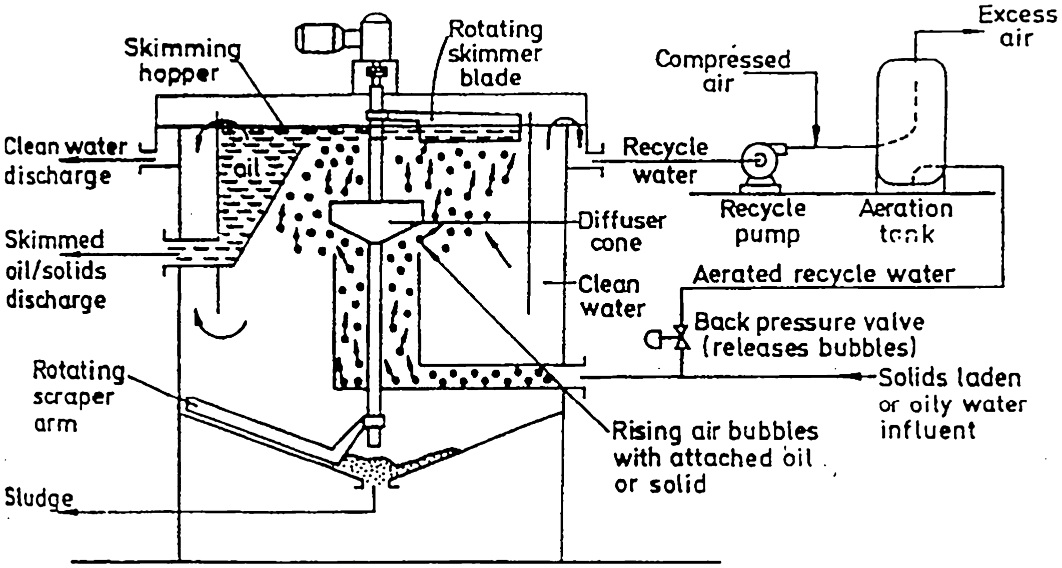


Fig. 18.6 Dissolved-air flotation equipment

intermediate baffles be used at right angles to the flow; these promote undesirable turbulence. A good depth for a large trap is 1.5 m; 2 m should be a maximum. This will give a surface loading of around 2 $m^3/m^2/h$.

Wastewater is led into the trap through a flow spreader and flows gently down the length of the trap to a fat-retaining baffle; the wastewater flows under this baffle and away to drain. Fat may be scraped off the trap periodically and settled grit should also be cleared from time to time.

Most fat traps are civil engineering constructions in the ground (due account needs to be taken of the acid nature of the waste), but it is also possible to design functional traps in GRP (glass-reinforced plastic), which can be floor mounted.

18.3.1.3 Aeration Equipment

Dissolved-air flotation equipment (Fig. 18.6) has a possible role as a fat separator, as a protein removal device, and for the general reduction of COD. Because efficient operation of the equipment depends on a number of mechanical components working satisfactorily in a wet and dirty environment, it should not be installed unless there is a serious commitment to maintaining it effectively.

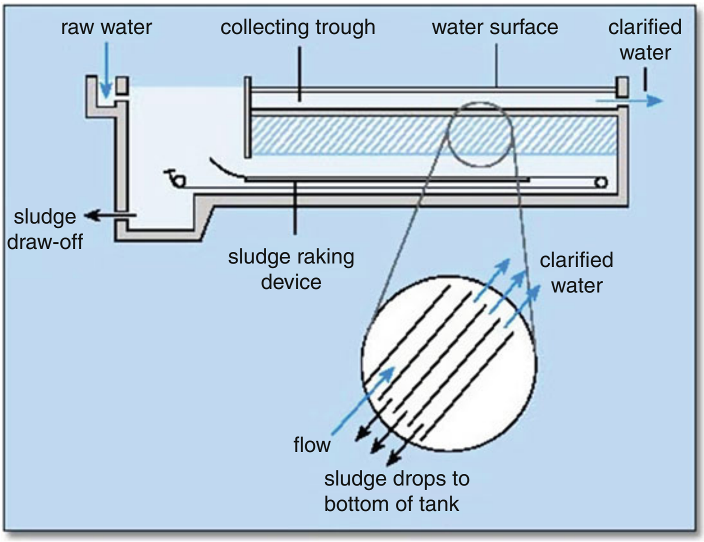


Fig. 18.7 Inclined plate separator (http://labspace.open.ac.uk/mod/resource/view.php?id=446118 © Open University)

In essence, pressurized air is dissolved into water, which is then added to the waste stream; as the pressure is reduced, the air comes out of solution and forms small bubbles. Fat, protein, and other dispersed solids are attracted to the surface of the bubbles, which coalesce as they expand while rising through the liquid. The solids form a delicate cap on the surface, which can be skimmed off.

The problems with the equipment are the delicacy of the cap, which can be strengthened by adding chemicals to the pressurized air/water system, and the mechanical challenge of maintaining the equipment. DAF plant is usually of circular cross section, which permits a more easily designed scraper system. The water in which the air is dissolved is runoff water from the unit. In some versions, air is introduced through a perforated medium to form the bubbles. In the author's experience, these are less satisfactory than the dissolved-air units. Electrolytes and other chemicals may be added to promote coalescence of the dispersed solids. The overall desirability and running costs of these additives should be considered.

When well maintained, these plants can have high efficiencies. The loading and retention times are about the same as those for a fat trap, with about 25 % of the runoff water being used in the recycle stream.

18.3.1.4 Inclined Plate Separator

An inclined plate separator (Fig. 18.7) consists of a large number of parallel plates set at an angle to the vertical. As wastewater flows up through the plate stack, fat and suspended solids may rise the quite short distance needed to bring them in contact with a plate where they coalesce and flow upwards in contact with the bottom side of the plate. These units have the advantage of being compact and without moving parts, but they are relatively expensive. Only limited information is available about their performance on food-industry wastes. They are unlikely to be economic in smaller factories.

18.3.2 Holding and Discharge

The primary treatments described above should effect removal of a substantial part of the material, which can be separated by physical means. If well selected and located, they should bring the fat and suspended solids requirements for the combined waste stream within the "Consent" conditions for discharge to the municipal sewer.

Consideration should be given to the provision of a holding tank of sufficient capacity to even out the effluent flow from the factory. This will help to keep it within the "1-hour volume" rate in the "Consent." A tank with a minimum of 4-h capacity may be adequate to even out the flow rate and "quality" of the effluent, particularly those changes that occur during cleaning and sterilizing operations (if possible, a 24-h capacity tank would be better). It will also be a convenient place to adjust the pH of the effluent and to sample. The simplest and cheapest additives for pH control are sulfuric acid and caustic soda. Both are dangerous chemicals and installations should be engineered accordingly.

The contents of the holding tank may be kept sweet and some reduction in COD obtained by the use of Venturi aerators in the base of the tank. These operate by withdrawing a small quantity of liquid from the tank and pumping it back into the tank through a Venturi, which draws in air with the liquid. This keeps the tank contents oxygenated and inhibits the growth of anaerobic bacteria, which would produce foul sulfurous smells.

In addition to the trade waste arising from production operations in the factory, there will also be:

- Foul drainage from the drains serving the personal functions of factory staff
- Runoff waters from drains collecting water and rainfall from factory roofs and roadways
- Cooling water (possibly)

Foul drainage should be kept separate from trade waste until the point of discharge from the factory. Runoff waters and cooling waters should also be kept separate. It may be possible to reach agreement for runoff and cooling waters to be discharged at low cost into a local water body (stream, canal, lake, or sea) subject to some controls on the level of contamination (this may require grit removal, a solvent interceptor, and reaeration). If an in-factory effluent plant is to be built, then it may be possible to exclude runoff and cooling waters from the biological treatment operations but include them in the tertiary treatment stage. The foul drainage would be screened and included with the trade waste stream for biological treatment.

18.4 Secondary Treatment

It has been explained above that there is usually a good case for some in-factory primary treatment of wastewater but there is no general justification for secondary treatment. Local municipal sewerage plants are large-scale operations run by specialists and are normally far enough away to reduce substantially any risk of bacterial contamination of the factory processes. There are, however, a number of circumstances when secondary treatment in-house is desirable, such as the absence of a local sewerage works with the necessary capacity or excessive charges. It is always helpful when considering the possibility of in-house secondary treatment if a suitable site for the treatment plant is available remote from the main factory operations with a suitable water body into which the treated effluent may be discharged. It is also helpful if surrounding land can be controlled so that houses are not built nearby, which could lead to complaints of smells and flies. Prior use is not a defense against complaints of "nuisance."

Fig. 18.8 Typical percolating (trickling) filter

The principle of all secondary treatment plants is to bring the effluent into contact with a population of bacteria, which will grow on and break down the organic matter in the effluent and which will proliferate. The degree of bacterial growth will depend on a number of factors such as temperature, the availability of oxygen, the concentration of organic matter, the pH, and the presence of suitable nutrients. An acidic pH tends to inhibit bacterial growth so that effluents from vegetable and milk factories may need to be adjusted by the addition of caustic to bring the pH into the desired range of 7.0–8.5. It may be necessary to add nutrients to higher-efficiency treatment plants. In theory, this could include a range of trace elements, but in practice it usually suffices to maintain an adequate level of nitrogen and phosphorus. Ratios of COD:N:P of 100:5:1 are generally satisfactory. Standard-grade fertilizer is quite suitable for this purpose. The cost of nutrients and of pH-correction chemicals should always be considered when working out the financial implications of in-house treatment.

Bacteria grow faster at higher temperatures but, as the temperature rises, different bacteria will tend to predominate. Generally aerobic treatment plants run at temperatures from 10° to 25°C, while anaerobic plants operate better at temperatures from 25 to 40 °C.

Modern high-rate aerobic plants using activated sludge need more oxygen than the older traditional trickling filter plants, but too much oxygen can lead to excessive growth of bulky sludge, which is difficult to settle and expensive to reduce for disposal.

18.4.1 Aerobic Digestion

18.4.1.1 Percolating Filters

Percolating, or trickling, filters (see Fig. 18.8), the familiar circular beds of coke or stone with a spray boom irrigation system, were traditional biological treatment devices. Bacterial and other growth build up on the packing and eventually fall off into the exit stream from which it is removed in a settling tank. These devices have a relatively low capacity per unit volume and are less effective in cold weather. They are prone to blockage by fibrous material (such as may arise in meat wastes) but they are simple and robust. In dairy-factory practice, their operational effectiveness has been increased by using them in tandem, with first one filter leading and then the other. This alternating double filter (ADF) system has been widely used for milk processing factories in rural areas. The ADF system can accommodate heavier loading and some quality variability. ADF systems can be considered for any effluent that does not contain fats or quantities of fibrous solids.

The loading limits for percolating filters are of the order of 400 mg/l COD and 0.3 kg COD/m^3/d.

18.4.1.2 Tank Fermenters

Tank fermenters were developed to meet the needs of the meat industry, but they are now widely used in various forms as compact treatment units for food factories. Good tank fermentation is greatly assisted by the availability of a good flocculent sludge. It is usually possible to import an initial load of suitable sludge from a local sewage works or other treatment plant. This sludge will adapt in a few days to the in-house effluent, and the art is then to maintain its flocculent character.

In this treatment process, the balanced waste stream is mixed with recycle, which contains the activated sludge, and the mixture is aerated by rotating discs, turbines, rotating brushes, or other devices. After a residence period, the waste is settled. The clear overflow may be run off to tertiary treatment, while part of the settled sludge forms the recycle. Surplus sludge is removed for disposal.

Tank fermenters depend for effective operation on a steady flow of effluent of consistent quality. Operation will be upset by sudden overloads, spikes of cleaning fluids, or contaminants such as diesel oil, hence the desirability of a good balancing tank. Control is possible by adjusting the level of recycled sludge and the rate of aeration. If the sludge bulks up too much, it will not settle and will therefore be lost in the overflow from the settling tank. As a result, there will not be enough active material in the recycle to the initial tank. A good sludge will have an SVI of less than 100; that of a poor sludge will be over 200.

An effluent of 1,500 ppm COD could be loaded at a rate of 0.5 kg COD/m^3/day with a residence time in the aeration tank of 24 h.

18.4.1.3 Contact Stabilization

There are four distinct stages in this variant of the tank fermentation process. The first two (mixing and aeration) are the same as those employed in standard tank fermentation. In the third stage, the drawn-off sludge is reaerated for several hours before most of it is recycled into the first stage. The surplus sludge is fermented in the fourth stage, an anaerobic digester, which reduces the content of organic matter.

The advantage of the process is that, because of the aeration of the recycled sludge, it is maintained at a higher level of activity and the initial contact time in the first stage of the system may be as short as 1 h.

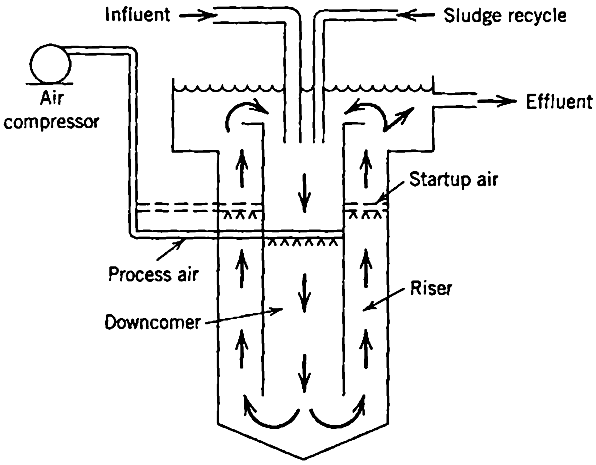
These fermenters may be quite compact and are sometimes built with the first three stages incorporated into a single tank fitted with suitable baffles.

The runoff liquid from the anaerobic digester will be recycled to the first-stage tank, while the digested sludge is disposed of periodically.

18.4.1.4 Oxidation Ditches

An oxidation ditch requires more space, but it is a robust operating system less affected by variations in quality and quantity of wastewater. The ditch is built as an oval about a meter deep with a brush aerator or some alternative, which not only provides aeration but also encourages flow

Fig. 18.9 Deep-shaft process (From Droste (1997), with permission)



around the circuit. The ditch will normally be excavated and lined with a synthetic rubber liner. Wastewater is fed into the ditch close to the aerator, and treated effluent is drawn off by a launder to settlement and further treatment prior to discharge. Aeration is controlled to maintain a suitable level of dissolved oxygen. Flow around the ditch is fairly slow (0.3 m/s) so there is not a great deal of mixing except at the aeration brushes.

18.4.1.5 Packed Towers

In a packed tower system, the wastewater is recirculated over packing in a tower at a rate that keeps the sludge well aerated and thus activated. Part of the downflow is recycled, while the rest is settled to constitute the treated water stream and the sludge removal fraction.

Although ceramic packings can be used, it is possible to build lighter, more efficient structures with proprietary plastic packings, which allow more evenly dispersed flow and thus a greater wetted area. These towers need to be suitably enclosed to prevent the carry-over of spray droplets and associated bacteria to adjoining premises or processes. The packing needs to be carefully leveled and the distributor kept clean so as to wet all the packing evenly and obtain maximum efficiency. High-recirculation rates may be needed.

These towers are extensively selected by the food industry as a first biological treatment stage for strong effluents and typically reduce the BOD by 60 %. It could be that, after such treatment, it is economic to discharge to sewer, so that further treatment is completed by the sewerage authority

18.4.1.6 Deep-Shaft Process

Although this process was developed in the UK, it has found its widest application elsewhere where its compact nature is more highly valued.

The deep shaft is from 50 to 150 m deep and is of a suitable diameter for the duty. As shown in Fig. 18.9, it is divided vertically into inflow and upflow sections. Air is injected initially into the upflow section, but, once circulation is established, this is switched to the downflow section, and the driving force is the change in volume and density due to the progressive expansion of the bubbles. The motion gives complete mixing and the air level is adjusted to give good digestion of the biological solids. As the waste emerges from the shaft, entrained gases disengage in an expansion tank and treated sewage is taken off for further treatment, while some may be recycled.

Given suitable geological conditions, these plants are robust and simple with a small footprint. The possible biological loading is high (4 kg BOD/m^3/day) and the retention time may be as short as 2 h.

18.4.2 Anaerobic Digestion

Thus far, the secondary treatment options considered have been for oxidative treatment of the wastewater. This leads to the production of carbon dioxide and relatively bulky bacterial sludges, which can be tricky to control and dispose of. In anaerobic treatment, the system is totally enclosed so that there is no free oxygen present and a different bacterial flora is developed, which breaks down the organic matter present, initially into simple acids (e.g., acetic) and then into methane and carbon dioxide.

Once anaerobic digesters have been started, they stabilize themselves and can be shut down for periods and restarted when required. This is useful for factories processing vegetables, where the processing campaign may be of relatively limited duration but involve considerable activity. Adequate pretreatment and the addition of nutrients are required, just as for aerobic treatment. In sewage works, batch anaerobic digesters have been in use for many years to digest sludges from aerobic activated sludge plant and thus to reduce the disposal burden. Disposal of sludges is becoming an increasingly significant problem with tighter regulation of disposal mechanisms.

Anaerobic digestion of food-factory wastes has only come into use in the UK in relatively recent years (since the late 1980s), and much of the expertise has been imported. There are now some very successful installations, but some caution is desirable in checking the antecedents of any proposed contractor.

An anaerobic digester is an enclosed vessel into which the effluent is pumped. The bacterial flora breaks the organic matter down into methane and carbon dioxide, and a gas stream is removed together with a liquid effluent containing some organic sludge. The digesters operate at quite low pressures but, being about 50 % methane, the gas stream should have a useful calorific value (24 MJ/m^3); some of this gas may be used to maintain the reactor at its optimum operating temperature of about 35 °C.

The digestion vessels are designed in a number of ways. In some, the bacteria are held on a filter medium. The waste flow may be upward or downward. There are also contact digesters and sludge-blanket digester designs (Fig. 18.10)—see also Foster (1994). Residence times for the liquid phase are of the order of hours, typically 6–20 h. The reactor loading may be of the order of 10 kg COD/m^3d. Successful applications have mainly been for treating wastes high in carbohydrate; wastes with significant protein content would tend to produce complex sulfur compounds during anaerobic digestion, which could present considerable odor-control problems and might adversely affect the performance of the digestion bacteria.

Two main groupings of bacteria grow under the anaerobic conditions: acid producers break down the incoming waste into soluble simple organic molecules, typically acids and ketones. Methanogenic bacteria further degrade these compounds to methane and carbon dioxide. At start-up, it is important to provide conditions, which encourage the growth of the slower growing methanogenic bacteria, and to avoid excess acidity.

Anaerobic digesters are generally designed to achieve in excess of 80 % removal of the organic load, with a downstream aerobic facility being provided to reach lower organic loadings if this is required. In some circumstances the anaerobic digester may be used to partially treat a waste stream before discharge to the main sewer in order to reduce charges. Partially treated effluent from an

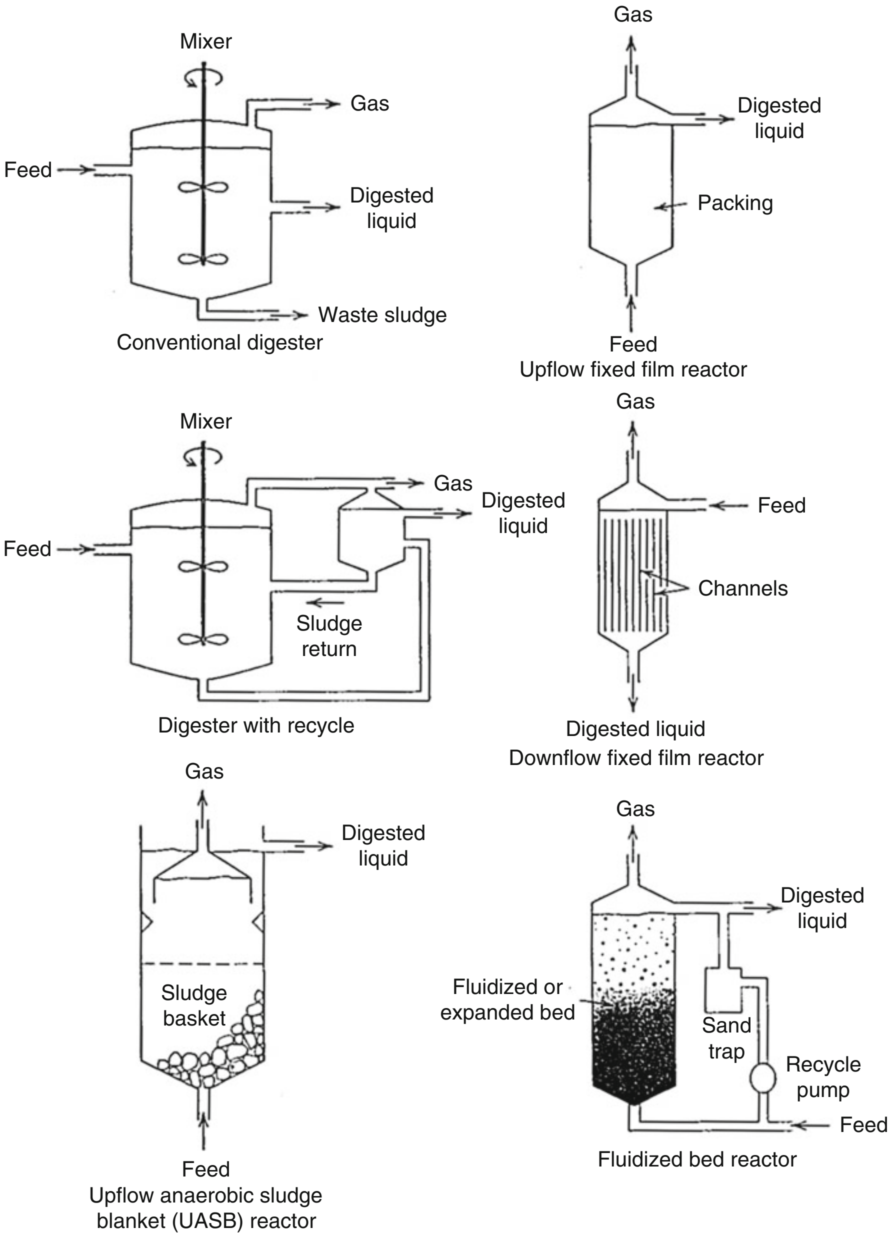


Fig. 18.10 Anaerobic digester designs (From Droste (1997), with permission)

anaerobic digestion plant may not be acceptable to the sewage authority because of the presence of inflammable, poisonous, or foul-smelling gases such as carbon monoxide, hydrogen sulfide, and methyl sulfides, which could be dangerous in sewers.

As has already been pointed out, there may be a case for treating a selected strong waste stream rather than the whole of the factory effluent. An anaerobic digester could be useful for this purpose.

Anaerobic digesters should be protected from potential bacterial poisons such as chlorine and cleaning materials.

18.4.3 Sludge Handling

It was previously accepted that food-industry sludges could safely be spread onto farmland, but this assumption is being increasingly questioned and other methods of disposal need to be considered. Disposal to the local sewerage authority may be an option, as it will also have a requirement to treat and dispose of its own sludges. Traditionally, some sewage works allowed sludges to settle and dewater over a period of months. The dried sludge was then dug out and disposed of. Such sludges could be burned.

Sludge volumes can be greatly reduced by anaerobic digestion and some sewage works adopt this option. Dumping at sea is no longer considered to be acceptable.

18.5 Tertiary Treatment

18.5.1 Introduction

Tertiary treatment is most often required when it is proposed to discharge an effluent to a water body without further treatment. The required standard for the wastewater discharge will be set by the authority responsible for the water body, which will itself be subject to a statutory duty to maintain the quality of its water.

The standard required will vary according to the nature of the water body and the quality objective that has been agreed or is set by legislation. In the UK, for instance, the standard required for discharge into water courses from which drinking water is to be drawn was for many years that set by a Royal Commission early in the 1900s of 20 ppm BOD, 30 ppm suspended solids. A better quality of discharge may now be required for many water courses. Again, there is a warning that failure to meet the set standard is a breach of contract and could, if continued, result in the discharge being stopped with serious implications for the continued operation of the factory.

18.5.2 Equipment for Tertiary Treatment

18.5.2.1 Lagooning

In a lagoon, the wastewater is stilled. This permits the solids to settle, while the large surface area will allow some bacterial action to continue, thereby reducing BOD. Lagoons should be shallow (0.5–2 m deep) allowing a residence time of 2 or 3 days. They are highly subject to the vagaries of the weather and close control cannot be exercised. Algal growth resulting in an increase in solids content can occur in warmer weather; this is not a problem if the residence time in the lagoon is not more than 2 days. Loadings of 1–3 m^3/ha/day are acceptable, depending on the quality of the effluent and the discharge standard required.

18.5.2.2 Irrigation (Spreading)

Wastewater can be further purified by spreading it on land. In the UK this is conventionally grassland. The wastewater is partly filtered by the vegetation and some of the water is absorbed by the soil. Rates of application can be higher in warm dry weather than when the ground is already saturated after rain. Loadings are about the same as for lagoons. Selected farmers may be pleased to receive this source of water and nutrients at certain times of the year.

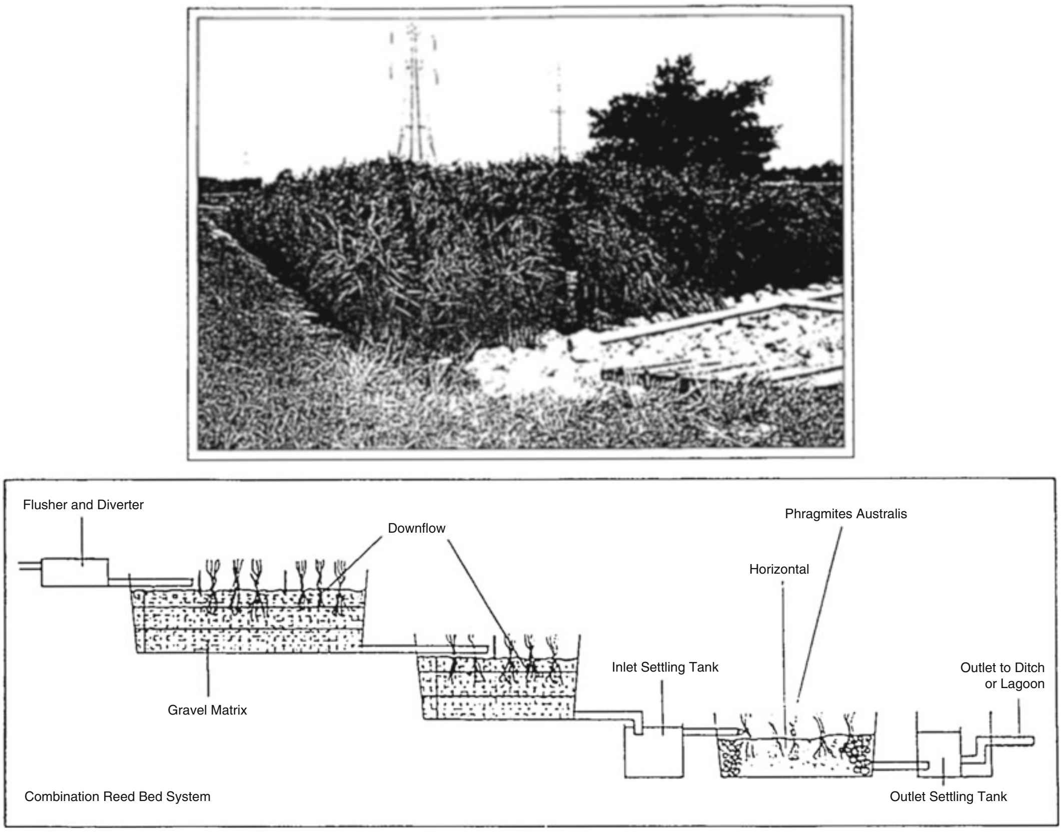


Fig. 18.11 Reed bed (Courtesy of ARM Group Limited, Rugeley, UK)

18.5.2.3 Reed Beds

Reed beds (Fig. 18.11) have been used to treat a wide variety of industrial and domestic wastes for more than 25 years. They are similar in concept and operation to natural wetlands. As such they represent a "green" approach to contaminated-water treatment and can be expected to be substantially more effective than irrigation or lagooning. A reed bed consists of a specially designed pond fitted with an impervious lining and underdrains, which is filled with sand, gravel, or soil or mixtures thereof to a depth of typically 300–1,000 mm. The media is planted typically with reeds of the Phragmites family. However, other marginal wetland species such as Iris or Typha can also be used. These do not provide the bulk of the treatment in themselves, but their root systems assist with maintaining pathways for the water to flow and provide minimal oxygen transfer into the root zone of the reed bed. This creates an ideal environment for colonies of microorganisms that degrade the contaminants in the effluent to become established by attaching themselves to the roots and the gravel, soil, etc. in the bed. The effluent to be treated enters the bed through an inlet pipe, which is often located at a level above that of the outlet to maximize head loss to facilitate flow through the bed.

Reed beds can be of any shape (e.g., rectangular, circular, or irregular) to fit the available land. They can be designed for aerobic or anaerobic conditions, depending on the nature of the contaminants to be removed and can work in a flooded or free-flowing mode. The residence time of the wastewater in the bed, which is determined by the flow, void space, and volume of the bed, depends on the nature of the contaminants being removed. For tertiary treatment, it is typically 2 days, longer if metals are to be removed. Although simple in concept, the satisfactory design of reed beds does require expert input.

Several different types of reed bed systems have been developed over the years (ARM 2013). Horizontal-flow reed beds are widely used and consist of single (or parallel) beds. They are suitable for reducing BOD and suspended solids (SS) levels in low-strength effluents but are not effective in reducing ammonia levels. The media in vertical-flow (or downflow) reed beds is often graded. Most consist of two beds operated in parallel, and, more often than not, they are dosed sequentially. Their footprint is often smaller than that of an equivalent horizontal-flow bed. Vertical-flow beds are typically free draining to maximize oxygen transfer. As a result, this design can handle stronger wastes and can reduce ammonia as well as BOD and SS levels. Forced Bed Aeration™ systems have been developed that yield significantly higher contaminant removal rates than the statically operated beds described above and also display an improved consistency of performance.

Reed beds do require regular maintenance to maintain the flow through the bed. Thus, dead reeds, weeds, and other rotting vegetation should be removed periodically. It may also be necessary to replace the entire gravel bed every 7–10 years.

Several texts on the design and operation of reed beds have been published, for example, Vymazal (2008) and Kadlec and Wallace (2009). The Constructed Wetland Association's website (CWA 2013) provides an extensive reading list on the subject.

18.5.2.4 Sand Filters

Nearly all sand filters now in use are of the rapid pressurized type, where wastewater is forced down through a bed of sand. The bed is cleaned periodically by backwashing with clean filtrate and air. These filters will treat 200 m^3/m^3/day. They will give a quality performance on a par with lagoons or irrigation.

18.5.2.5 Strainers

A modern alternative is the use of a fine metal fabric to remove suspended solids. The fabric is held on a rotating drum through which the wastewater passes. It is cleaned by backwashing the drum with filtrate at its highest point of rotation, the recovered solids being flumed off for recycle.

18.6 Summary

The disposal of wastes costs money: only by devoting an appropriate amount of management time to the problem can these costs be minimized. Shortcuts can lead to major problems affecting the continuity of production.

It is important to provide adequate specifications for any effluent treatment facility. Table 18.1 provides suitable guidelines.

Managers and staff will need to be well trained, motivated, and supervised, recognizing that the effluent plant can be a source of contamination of factory product. Consideration should be given to the use of the management principles set out in the environmental quality standard ISO 14001.

Acknowledgements Information included in this chapter has been derived in part from a training course run over a number of years at Leatherhead Food Research and includes information provided by M. Hemming of Allott Environmental Processes Ltd, Manchester, and by Dr A. Wheatley of Loughborough University.

References

ARM (2013) ARM Ltd, Rydal House, Colton Rd, Rugeley, Staffordshire, WS15 3HF, UK, http://www.armreedbeds.co.uk/resources/constructed-wetlands/.

CWA (2013) "Recommended reading", Constructed Wetland Association, Rydal House, Colton Rd, Rugeley, Staffordshire, WS15 3HF, UK, http://constructedwetland.co.uk/resources/recommended_Reading/.

Droste, R.L. (1997) "Theory and practice of wastewater treatment", John Wiley & Sons, New York, 800 pp.

Foster, C. (1994) "Anaerobic digestion and industrial wastewater treatment", Chemistry and Industry, June, pp. 404–6.

Kadlec, R.H. and Wallace, S. (2009), "Treatment wetlands", 2nd edit., CRC Press, Boca Raton, FL, 1016 pp.

Oasis (2012) "Mogden formula", Oasis Environmental Ltd, Manchester, UK, www.oasisenviro.co.uk/mogden_formula.htm.

Vymazal, J. (2008) "Wastewater treatment, plant dynamics and management in constructed and natural wetlands", Springer Science+Business Media, New York, 348 pp.

Part IV
Project Engineering and Management

Chapter 19
Role of the Project Engineer in the Design Stage

G.M. Kirt

19.1 Introduction

> Project Management is about change. Projects are one-off initiatives conducted in short time-scales for which there are no rehearsals and few precedents…

The term "Project Engineer" is widely used across all industries and organizations. Its precise definition, however, varies tremendously from manufacturing, IT and consultancies, at one extreme, through public utilities, educational establishments to noncommercial organizations at the other. Most online and published trade journals, professional publications, and daily newspapers carry advertisements for project engineers.

Whilst there are wide interpretations, there are also some common factors. Projects by their very nature are extraordinary events. They are rarely repeated in precisely the same format. They often demand resources beyond the normal day-to-day structures. The required input will cross many organizational boundaries and often involve external resources and specialist expertise.

So what are the key characteristics of a project engineer? There are many published works, which explore the personal and professional attributes of individuals suited to the role. However, if these were catalogued into a profile, nobody would ever meet the demanding requirements: multitalented, widely experienced, resourceful, unflappable, team player.

In reality, all project engineers need support and help from within the organization and also from external sources. Successful projects will always be the product of a broadly based team. Throughout the life of a project, from concept to completion, the lead role will change and may even pass from individual to individual. The responsibilities may move from internal to the organization to external agencies. This may involve the drawing up of formal contracts, which define the roles and responsibilities, or only be an informal arrangement between the parties.

This chapter therefore does not attempt to describe the role of the project engineer. Rather, the activities that must be addressed are described, together with guidelines to avoid misunderstandings and potential overruns in time and costs.

G.M. Kirt (✉)
Protel Associates Ltd, 5 Rectory Lane, Glinton, Peterborough PE6 7LR, UK
e-mail: gerardk@protelprojects.com

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_19,

The actual responsibilities of all parties must be clearly understood and, if the lead role changes from individual to individual, there must be a seamless transfer with obvious transparency in the handover. Throughout the life of a project there is one golden rule:

> In all project related matters my allegiance is to the Project Objectives which take precedence over functional loyalties.

Of course, there will many who claim that professional responsibilities for health and safety, environmental, commercial confidentiality, etc., must take precedence. This is of course true but a strong allegiance to the project does not mean that professional standards are compromised, quite the reverse. Indeed the exercise of appropriate checks and balances from specialists is essential to achieve project objectives, which, at all times, must embrace corporate and statutory obligations.

Project allegiance means the common ownership of time-scales, critical success factors and target cost estimates by all parties involved. In the same way that a sportsman or sportswoman selected for a national squad has a strong motivation for the national team to win, but does not sever the links with their home club team, so too project team members are focused on project success.

This then, perhaps, is the simple role of the project engineer:

> To motivate all team members to exercise their particular skills in the single-minded objective to meet the project objectives.

This chapter explores the role of the project engineer in ensuring that the project scope meets the needs of the ultimate user and that the defined scope is properly communicated to the specialist design resources. Techniques are presented which will help minimize the risk of misunderstanding, delays, and budget overruns. At all stages of a project from concept to completion the Project Management function is critical to successful implementation.

Before defining the project engineering activities in more detail, it is important to understand the various stages in the life of a project. The roles and responsibilities will vary throughout the various stages.

19.2 The Investment Cycle

Is your working life punctuated by corporate rituals? These events are common throughout most organizations and are not restricted to commercial enterprises. You will be familiar with the 3-year planning cycle, the budgeting processes, the monthly search for explanations, the half- and full-year results, another marketing plan, etc. Each of these milestones requires the senior management of the organization to step back from their day-to-day activities and consider how the future might unfold in the light of current performance, recent history and the planned changes.

Sometimes it seems that all the time is taken stepping back and planning, and little time is left to actually manage and implement the agreed actions. Recent pressures to reduce overheads, downsize and out-source specialist skills leaves key managers under-resourced to carry out both the planning and the implementation of the strategic changes essential to achieve more efficient organizations and facilities.

Change is essential and unavoidable. Change must be regarded as the norm. Change can be required because of growth, new technology, acquisition, new products, customer demands, yet another marketing plan, etc. Some of these changes will result in the need to physically alter the manufacturing and distribution facilities. Such investments need to be carefully planned and professionally implemented to avoid delays, over-spends and to achieve the desired quality standards.

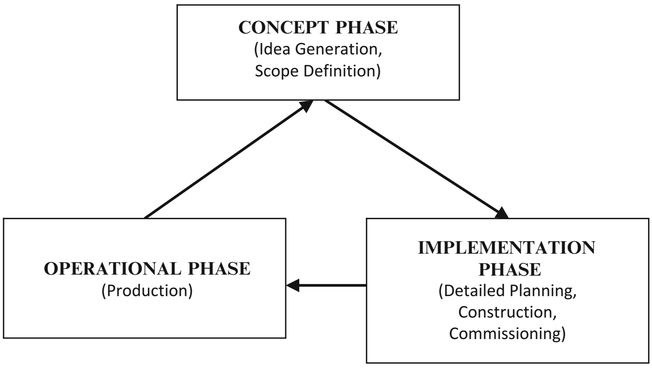


Fig. 19.1 The investment cycle

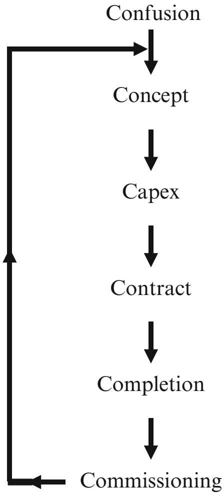


Fig. 19.2 The six "C"s

The "Investment Cycle" (Fig. 19.1) highlights the cyclical nature of all capital investments. No sooner is one project complete then the search for further improvements should begin. The key to success is to ensure that the stage from "Idea Generation" to "Scope Definition" is thoroughly carried out.

In the absence of in-house resources to develop the investment project concepts and to secure the agreement of all the stake-holders, there is grave danger of jumping from the ideas for change stage straight to a contract for implementation. As a result, this will be ill-defined, have inadequate contract safeguards and a loose project program. Cost overruns and delayed completion are an almost inevitable outcome of such projects.

Organizations often turn to consultants to help define the strategic imperatives for corporate change and then leap into contracts with specialist suppliers of plant, machinery or systems. The whole process from corporate strategy to project completion should involve an holistic approach, with all aspects and implications being explored. The key stages are shown in Fig. 19.2, which identifies the six C's in the investment cycle that are necessary to achieve the successful investment.

So the project engineer's role starts with confusion. What are the key drivers for change? What are the project objectives? What are the success criteria?

From an analysis of current circumstances will come the identification of opportunities for change. These opportunities will address issues of efficiency, capacity, and introduction of new products as well problems of hygiene and noncompliance with recognized codes of practice. In order

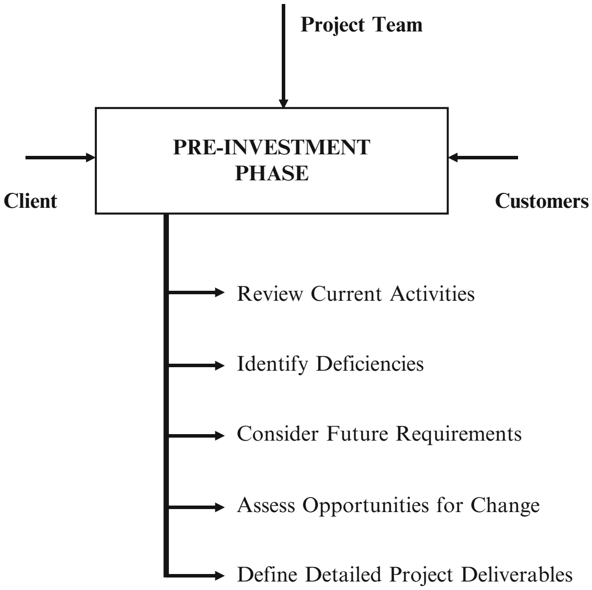


Fig. 19.3 Pre-investment activities

Table 19.1 Opportunities for change

- Capacity increases (or consolidation)
- Reconfiguration
- NPD introductions
- Cost savings
- Legal, safety, hygiene
- Essential replacements

to gain approval to invest, a package of measures is often included. Some of these measures will result in cost savings and/or capacity increases. Others may not contribute financial benefits but are essential to maintain current levels of business and meet legislative and customer expectations.

The pre-investment phase of any project (Fig. 19.3) should first of all review current activities and identify the deficiencies associated with both operational and noncompliance issues. The consideration of future requirements will identify the opportunities for change. These can be categorized as shown in Table 19.1. Most projects will include elements of all of these. The project deliverables must also be clearly developed and defined during the course of the pre-investment phase. Normally, improved operational efficiencies and greater flexibility can be achieved even if the primary focus is to upgrade the facilities and improve GMP.

Once the opportunities have been identified and the strategic imperatives for the investment project agreed, there is an understandable desire to move directly to the implementation phase. This could involve the purchase of new plant and machinery as well as making improvements to the fabric of the building and the development of new amenities. However, the scope of works needs to be clearly and unambiguously defined, otherwise the cost estimates will be inaccurate and the project will be at risk of overruns and delays. Furthermore, unless the operating staff are fully committed to the changes and the customers have concurred with the proposals, the achievement of improved GMP will be jeopardized.

The pre-investment phase of any project, particularly those that involve significant changes to operating procedures, must involve close co-operation between all interested parties. The methodology adopted usually includes one-to-one interviews, group workshops, customer reviews and visits to similar establishments where changes have already been implemented. The key is to manage all these inputs within the context of a defined aspiration, which is compatible with the particular needs of the particular product sector and not just blind adherence to a set of general standards.

Table 19.2 Typical deliverables in the pre-investment phase

- Schematic flowsheets
- Schedule of space planning
- Equipment schedule
- Utilities demand projections
- Material flows analysis
- Stock holdings and turnover
- Dilapidation survey
- Identify options for change
- Layout for each option
- Hygiene zoning
- GMP regimes
- Cost estimates
- Implementation program
- Anticipated cash flow
- Cost–benefit analysis
- Cost-saving opportunities
- Future requirements
- Contingency plans
- Presentation documents

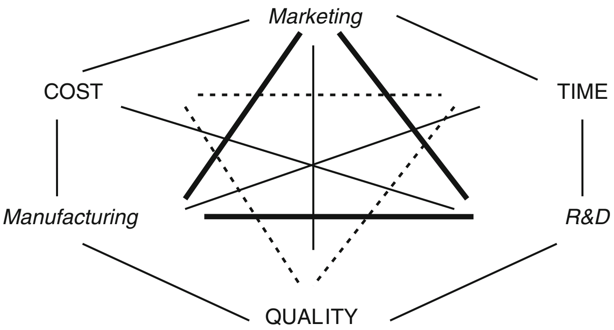


Fig. 19.4 Essential elements of successful project management

Some typical deliverables are set out in Table 19.2. The project engineer needs to draw together all the different aspects of a project and dissect the cost–benefit relationship for each of the aspects.

The preparation of a Capital Investment Proposal will need to cover the key drivers and potential benefits of the investment. In the Food Industry it is difficult to predict future demands and to forecast the likely sales volumes of new products. The financial justification of the proposed investment will therefore require a sensitivity analysis in which the implications of downturn in volumes can be modeled. Often the project engineer will need to develop contingency plans so that the investment can be justified even in the worst case scenarios.

The "Design Stage" of a food factory project therefore starts right at the beginning when the opportunity is first identified. The concept stage, prior to the sanction of the project, is critical. It is at this stage all the key aspects are defined and the success criteria agreed. The three essential elements of successful project management are defined at this stage. These are time, cost, and quality. Figure 19.4 illustrates the interaction between functions necessary to achieve success.

The implications of this diagram are far-reaching and they illustrate the greatest challenge to the project engineer, i.e., securing agreement of all parties to the scope of the proposals. The allegiance of Marketing, R&D and Manufacturing to a common set of project objectives is important. In particular, the defined objectives relating to time-scale, costs and quality are critical. For these purposes the term "Quality" embraces all issues relating to the functionality and reliability of the proposed plant to produce food products, which meet the defined quality standards and are safe, legal and satisfy customer and consumer expectations.

19.3 Detailed Design Stage

The preparation of the documentation required for sanction will vary from organization to organization but in all cases there will be a need for a schedule of anticipated costs. This will be prepared from budget prices for proprietary equipment, a preliminary bill of quantities for building works, and estimates based on experience of similar projects, e.g., for cold stores, warehousing. Also included in the cost schedules will be allowances for unforeseen items, foreign currency exchange rate fluctuations and contingency funds.

Value Management has an important role to play at the early stages of the project. It is important to differentiate between "Value Engineering" and "Value Management."

Value Engineering is concerned with achieving a given function at minimum cost. It is based on the assumption that the function is an objective characteristic, which is waiting to be identified. Furthermore, it is assumed that all feasible design alternatives provide the same level of functional performance and can therefore be assessed on the basis of cost alone. Within this frame of reference, an increase in value can be directly related to a reduction in cost.

Value Management, on the other hand, is concerned with defining what "value" means to a client within a particular context. This is achieved by bringing the project stakeholders together and producing a clear statement of the project objectives. Value for money can then be achieved by ensuring that the design solutions evolve in accordance with the agreed objectives. In essence, value management is concerned with the "what" rather than the "how."

The role of the project engineering function therefore is to ensure that the best value is achieved. The pre-capital investment (capex) studies will have identified that particular issues could be resolved and that the authorized funds would be adequate to develop an acceptable solution. Value Management exercises will not only achieve the project objectives but will also provide a vehicle for early team building and buy-in from team members.

It is often at this stage that specialist resources may need to be added to the project core team. Input to the design process will be required from, for example, structural, mechanical and electrical engineers. A detailed design program must be prepared, which will define the required input and the key time-scales.

The management of specialist design resources is an important aspect of this stage and an experienced design manager may be needed. This is one example of where the lead role may pass from the project engineer to another individual. Alternatively, the project management activities could be shared, with the design leader managing the design and the project engineer ensuring time-scales are met, buy-in is achieved, costs issues are resolved and the communications are flowing smoothly.

Some codes of practice, e.g., ISO 9000, require a "Project Quality Plan" be developed to cover the design stage. This will lay down the responsibilities of the team members and the communication network that will be applicable to the particular project. The scope of design reviews, the attendees, the circulation of minutes, etc., will all be defined in the "Quality Plan." It is good practice to prepare such a plan even if the company standards do not define a specific requirement.

Prior to the approval of any project, the "User Requirements" will have been considered. This pre-investment phase is most important, regardless of whether the proposals relate to a green-field site or to an extension to or alteration of existing premises.

The concept design will form the basis of the cost plan for the project. This cost plan, together with the operating rationale, will be the basis of the "Sanction to Proceed."

Unless the building design is thoroughly defined, the cost plan is likely to be inadequate. The design should incorporate those aspects of construction and finishes, which will be expected by customers and the statutory authorities alike. The preliminary stages of building design start with a clear and unambiguous description of the use of the completed facility. This user requirement can be described as the means to define the scope of the project:

> . . . in order to be able to prepare reliable forecasts on investment, production and marketing costs. As industrial projects often extend beyond the boundaries of the production plant site it is necessary to define the battery limits of the project. . . . The main reason for this is to force the project planner to look at material and product flow not only during the processing stage but also during the preceding and succeeding stages. . . .

Table 19.3 Stages of building design

- Define project objectives
- Analyze material flows
- Preliminary schematics
- Concept layouts
- Define hygiene zones
- Agree finishes schedule
- Check codes of practice
- Confirm statutory requirements
- Develop cost plan
- Project financial appraisal
- Capex preparation
- SANCTION TO PROCEED
- Detailed design

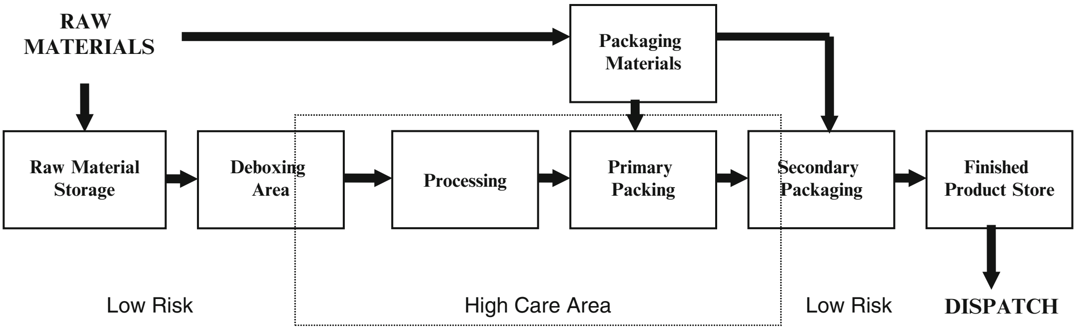


Fig. 19.5 Typical illustration of analysis of "Hygiene Zoning"

The various stages of building design are summarized in Table 19.3.

From consideration of the material flows, and the activities anticipated at each stage of the production process, specific areas can be defined, which will require different approaches to building design. Clearly areas for material receipt and storage will be different from the processing areas. The relationship between different areas will also need to be defined. The most obvious example is the location of personnel facilities (toilets, changing rooms, restaurant, etc.) in relationship to a "High Care" production area and the need for a "Hygiene Junction" with defined procedures for hand washing and changing. Figure 19.5 illustrates the zoning of a typical food factory.

Codes of Practice prepared by the major customers give advice regarding the zoning of specific areas and the finishes required. For example, the Standard developed by the British Retail Consortium (BRC 2011), which is now used worldwide, states:

> Premises and plant shall be designed, constructed and maintained to control the risk of product contamination and comply with all relevant legislation. The product flow from intake to dispatch shall be arranged to prevent product contamination.... There shall be an effective segregation between high and low risk operations.... Segregation shall take into account the flow of product, nature of materials, equipment, personnel, air flow, air quality and services provision.

The project engineer must ensure that these GMP aspects are thoroughly considered in the design stage of the project.

The design of buildings for the production of food products therefore starts with the detailed consideration of the material flows, hygiene zones and the codes of practice. Some sectors of the food industry have specific requirements defined in legislation. For example the egg processing, meat, dairy, and other sectors have legally binding obligations. Overall there is a requirement on all food producers to exercise due diligence, i.e.,

> ...he took all reasonable precautions and exercised all due diligence to avoid commission of the offence...

The food industry covers a wide range of activities from the handling of produce at the farm, bulk processing of primary ingredients (e.g., sugar, vegetable oil, flour milling) through to the final

Table 19.4 Generic types of food premises

- Raw materials receipt and externals
- Raw materials storage areas
- Bulk storage silos and tanks
- De-boxing, de-bagging, decanting
- Primary processing areas
- Secondary processing
- Primary packing
- Secondary packaging
- Packing material stores
- Product warehousing and dispatch
- Toilets and changing rooms
- Personnel “Hygiene Junctions”
- Amenities (break-out, restaurant, etc.)
- Services and utilities
- Offices and administration

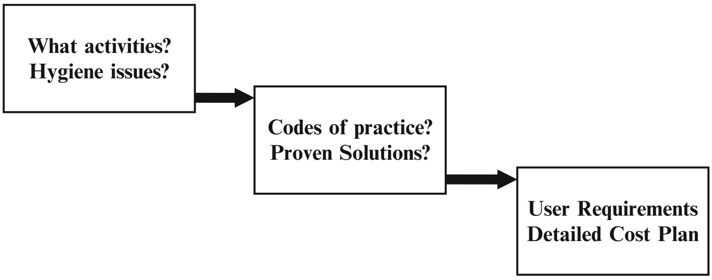


Fig. 19.6 Aspects of building design

preparation of ready meals in the final packs for sale to the consumer. It is therefore impossible to precisely define specific standards, which will be applicable in all circumstances. Each situation needs to be considered separately and building design standards adopted to suit the particular circumstances, the demands of the customers, and statutory obligations. Above all the implications for food safety should be top of the design criteria.

However, by consideration of recently completed projects, a range of designs and finishes can be reviewed and the most appropriate solution found for the particular application. This approach will ensure the details of the design are proven and that the techniques adopted provide facilities satisfactory in use.

The classification of building design into generic types (see Table 19.4) with particular specifications will enable the project scope and cost plan to be more accurately defined prior to sanction. This approach will also ensure that the operating staff can see the building types in operation at completed facilities. This will avoid any misunderstandings and reduce the likelihood of changes to the scope later in the design process.

The keys to understanding the scope of the design of buildings for food production are a clear definition of the activities involved, proper consideration of the codes of practice, a review of solutions implemented elsewhere in the industry, and a thoroughly described user requirement supported with a detailed cost plan. These aspects are illustrated in Fig. 19.6.

The project engineer will need to guide the project team through this process of analysis and consideration of the design details. The concepts will result in user requirements for issue to the specialist designers. This stage will need to be separately defined in the design program and progress regularly monitored by the project engineer.

The design of food factories must address all the usual issues of building design (Table 19.5). Many of these are statutory requirements; others are related to the particular policies of the client company (e.g., fire insurance requirements). These standard issues will influence the design and layout of the building. Aspects that require careful attention will include the provision of acceptable means of escape for operating personnel. Zoning of the premises to avoid the spread of fire may be in conflict with the desired hygiene zoning. Often these conflicts can be overcome and an acceptable solution found which meets both requirements. However, in considering building design, the safety of personnel must take precedence over any other aspects, including food safety.

Table 19.5 Building design issues

- Planning permission requirements
- Building regulations
- Environmental issues
- Utilities supply
- Fire protection
- Security
- Traffic and highways implications
- Car parking
- Disabled access
- Neighborhood aspects
- Noise
- Hours of operation
- Insurance
- Financial issues
- Leasing options
- Potential future activities

As well as these issues, which relate to all developments, there are particular requirements, which apply to specific sectors of the food industry. Some of these are defined in the relevant legislation; other aspects are included in the codes of practice of particular trade sectors or by the customers. No attempt is made here to be exhaustive and define particular standards. Each development should be considered in the light of the guidelines and experience of similar applications.

In most countries there is an extensive body of food safety legislation pertaining to all aspects of production and sales. An up-to-date list of UK legislation (from 1959 to the present day) has been published on the Internet (Dukes 2012). The Web site lists all relevant legislation that has been passed from 1997 onwards. Before this, only that legislation which was in force in 1977 is given. Links are provided to the individual bills. Leatherhead Food Research (www.leatherheadfood.com) maintains a database of global food law spanning over 80 countries. This organization is able to provide advice on maintaining compliance with local food regulations.

The expressions "all reasonable precautions" and "all due diligence," which feature in food legislation, are not specifically defined. However, the general understanding (based on case law) is that the expression "all reasonable precautions" means that a control system must be established, and "due diligence" means that steps are taken to ensure that the system is working satisfactorily. Such a system includes compliance with the law relating to all materials used, checks at every stage, cleanliness and hygiene of the buildings, machinery and instruments, training of staff, dealing with complaints, staff management, etc.

19.4 The Contract Stage

At an early stage in the design process, the project engineer will need to consider how the project will be implemented. There are a wide number of options for the construction. The particular route chosen will influence the design stage of the project.

The design and construction of food factories is usually carried out by specialist organizations working for the manufacturing company. There are several ways of bringing a building design to completion and then appointing contractors to implement the design through construction. The traditional route involves the separation of design from construction. The client will appoint consultants to prepare the detailed design and the tender documentation, and possibly undertake site supervision duties. The appointment of the design team occurs either by negotiation or competitive tendering. Contractors are selected by competitive tendering against the ITT (Invitation to Tender) documents.

The turnkey approach ensures that the whole process of design, specification, construction, and commissioning is carried out by one contractor. This approach depends on a precise definition of the scope of works prior to the appointment of the main contractor. Failure to do this may lead to scope for variations in cost or timing. Standard forms of contract are available for both these approaches as well as other methods of implementation.

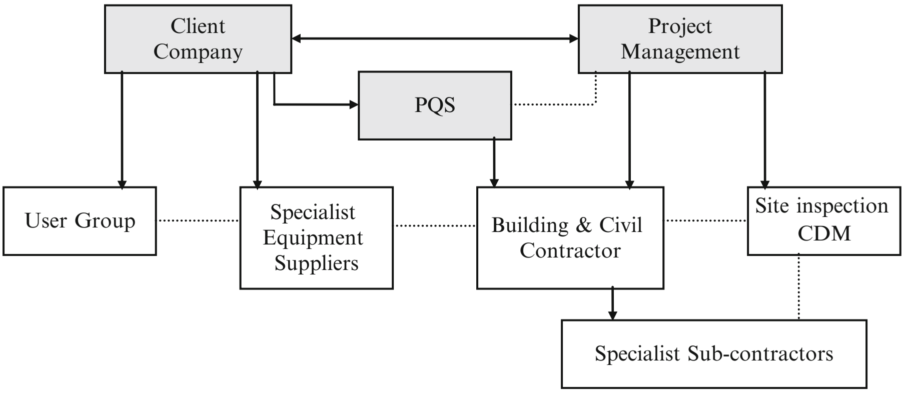


Fig. 19.7 Project management responsibilities

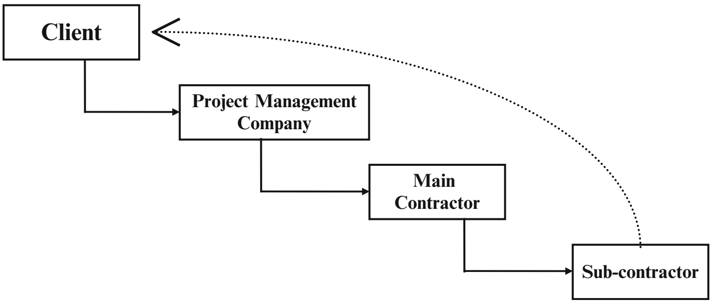


Fig. 19.8 Interactions between parties involved in a food-industry construction project

The project engineer will also need to consider how the responsibilities are shared with the construction personnel. One approach often used in the food industry is illustrated in Fig. 19.7. In this, the project engineer will appoint a project management organization, which will ensure that all operational issues are properly included in the User Specifications and that, throughout the whole project, the needs of the client company are safeguarded. This will include liaison with planning authorities, user groups, and possibly customers.

The ITT documents and the tendering process will be handled by the Project Management company. A Principal Quantity Surveyor (PQS) appointed directly by the client will provide the rigor and transparency necessary to ensure adherence to the cost plan and to control variations.

Throughout the length of the project, the allocation of responsibilities needs to be well understood. The contract documentation should ensure the achievement of functionality in actual operating conditions is the responsibility of specific companies on a back to back arrangement with the client company (Fig. 19.8).

19.5 Conclusion

This chapter describes the processes by which a capital project in the food industry can be brought from concept to completion. Whilst it is impossible to cover all eventualities and all types of investment some principles apply to all.

Success will require the allegiance of all members of the team to the project objectives. Aspects of project timing, costs, and functionality need to be commonly understood. Project success factors need to be clearly defined.

Above all, the pivotal role of the Project Engineer must never be undervalued.

Literature Cited

BRC (2011) "Global standard for food safety", Issue 4, British Retail Consortium, published by The Stationary Office, London.

Dukes, D. (2012) "UK food regulations – Chronological listing – Current", The University of Reading, www.foodlaw.rdg.ac.uk.

Kelly, J.R, Male, S. and Graham, D. (2004) "Value management of construction projects", Wiley-Blackwell, Oxford, 384 pp.

Further Reading

Adams, J.L. (2001) "Conceptual blockbusting: A guide to better ideas", 4th edit., Perseus, New York, 220 pp.

Brandon, P.S. (1982) (ed.) "Building cost techniques: New directions", E & F.N. Spon, London, 476 pp.

CIRIA (1983) "Buildability: An assessment", Construction Industry Research and Information Association, London.

Dell'Isola, A.J. (1982) "Value engineering in the construction industry", 3rd edit., Van Nostrand Reinhold, New York, 364 pp.

Ferry, D. and Brandon, P. (2007) "Cost planning of buildings", 8th edit., John Wiley & Sons, Hoboken, NJ, 432 pp.

Flanagan, R. and Norman, G. (1983) "Life cycle for construction", Surveyors Publications, London, 128 pp.

Halpin, D. (2010) "Construction management", John Wiley & Sons, Hoboken, NJ, 480 pp.

Kharbanda, O.P. and Stalloworthy E.A. (1988) "Capital cost estimation in the process industries", Butterworth-Heinemann, Oxford, 392 pp.

Lock, D. "Project management", 9th edit., Gower, Farnham, UK, 520 pp.

Nolan, V. (1989) "The innovator's handbook", Penguin Books, New York, 324 pp.

Peters, T.J. and Waterman, R.H. (2004) "In search of excellence", HarperBusiness, New York, 400 pp.

Potts, K. (2008) "Construction cost management: Learning from case studies", Taylor & Francis, New York, 306 pp.

Younker, D.L. (2003) "Value engineering: analysis and methodology", Marcel Dekker, New York, 326 pp.

Zimmerman, L.W. and Hart, G.D. (1982) "Value engineering: A practical approach for owners, designers and contractors", Van Nostrand Reinhold, New York, 279 pp.

Chapter 20
Role of the Project Engineer in the Construction Stage

G.M. Kirt

20.1 Introduction

The project is approved and the scope is defined. All that remains is to build the facility. If the pre-construction activities have been thoroughly carried out then the construction stage of a project should be straightforward, even if complicated. There will, of course, be the usual issues relating to consents, effects of adverse weather, and site management. If the construction is taking place on an existing site, then the avoidance of disruption to current operations will be important.

Project objectives will be compromised if any changes are introduced in the post-contract period. This will lead to "variations" which will undoubtedly result in additional expenditure and possibly cause delays to the program.

The first challenge to the project engineer in the construction stage is, therefore, to confirm that the project scope, summarized by the headings listed in Table 20.1, is well understood by all parties. In particular the concept scope should be reflected in the cost schedules, with allowances made for unforeseen aspects. The project objectives should be shared with the construction team members. The business aspects will be reinforced if explained by the client's key managers, including those concerned with the marketing aspects. The scope can then be included in the "Employer's Requirements" as part of the construction contract documents.

The particular type of construction contract will define the style and content of the project specification documents. In all cases, it is good practice for the description to be prepared, circulated, and signed off by all parties.

Following the review of the pre-construction activities the scope of the project will be defined. The program will be agreed and a target cost estimate developed. The project engineer needs to ensure that the construction team is fully aware of the details and that the contract documentation properly reflects the client's objectives and critical success factors.

There will be some overlap between the design stage and the construction stage and the method of incorporating detailed design onto the construction plans needs to be defined.

Some allowances included in the cost estimate will need to be clarified once the design is confirmed. For example the Room Data Sheets are not normally defined until later in the process and the impact on costs will have to be incorporated as soon this information is available.

The development of a Quality Plan (see Table 20.2) will lay down the procedures for the particular project. It will include a communication plan, requirements for quality checks and

G.M. Kirt (✉)
Protel Associates Ltd, 5 Rectory Lane, Glinton, Peterborough PE6 7LR, UK
e-mail: gerardk@protelprojects.com

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0_20,

Table 20.1 Pre-construction checklist

- Concept description
- Project objectives
- Critical success factors
- User requirements
- Performance criteria
- Mass balance
- Schematic flowsheet
- P&IDs
- Control concept
- Layouts and hygienic zones
- Schedule of finishes
- Utility demand schedule
- Project battery limits
- Functional specifications
- Equipment schedules
- Model form of contract
- Program
- Target cost estimate

Table 20.2 Contents of quality plan

- Team members
- Authority levels
- Communication plan
- Meeting schedules
- Key milestones
- Quality criteria
- Inspection procedures
- Health and safety responsibilities
- Documentation
- Variation procedure

certification of work completed. The quality plan will also define authority levels. This is particularly important if members of the client's management wish to suggest post-contract changes.

The review of project scope and preparation of a project quality plan will ensure that the construction stage of a project can be approached with confidence. A detailed program will need to show all activities with assigned responsibilities. Key dates for client reviews should be shown with allowances for discussions during the review period. It should never be forgotten that the client's managers will have other responsibilities and adequate notice and time should be allowed.

At this early stage of the construction it is helpful to give consideration to briefing the client's workforce. Descriptions of the proposals, outline time-scales, and where the construction could impact on their operations would be helpful. If ownership of the future workforce (the ultimate client) can be secured early in the project, this will pay great dividends at the hand-over stage.

20.2 Construction Contracts

Following approval of the investment proposals, the project engineer will concentrate on the design stage of the project. The type of construction contract must be considered early in the process to ensure that the content and style of the design documentation is compatible with proposed contract route.

The types of contract can be classified according to the manner in which payment is made. The two types commonly used for food factory construction are "traditional" and "turnkey." As indicated in the previous chapter, the "traditional" route involves the separation of design from construction. The client will appoint consultants to undertake the detailed design, prepare the tender documentation and, possibly, to supervise construction on site.

The appointment of the design team is either by negotiation or competitive tendering. Contractors are selected by competitive tendering against the ITT documents. The main contractor may be approached on a "fixed price" or "cost reimbursable" basis, depending on how well the scope and specifications are defined. As illustrated in Fig. 20.1, the contractor assumes most of the risk in the case of a fixed price contract; in contrast, the client bears the risk in a cost reimbursable contract.

The "turnkey" approach ensures that the whole process of design, specification, construction and commissioning is carried out by a single contractor. This approach requires a precise definition of the scope of works prior to appointment of the main contractor if "variations" in cost or timing are to be avoided.

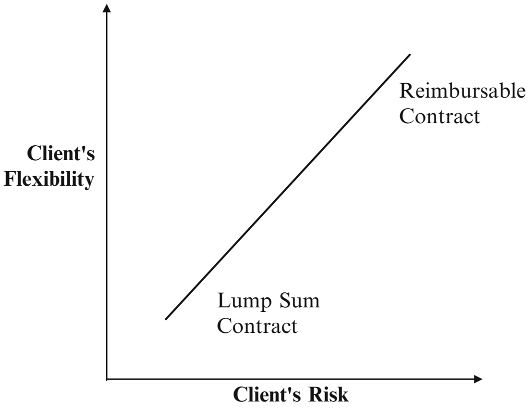


Fig. 20.1 Types of construction contract

Standard forms of contract are available for both these approaches as well as for other methods of implementation. In all cases, the more precise the design, the more certain are the anticipated costs of implementation.

There are three issues the project engineer needs to address. These are:

Incentive: To provide an adequate incentive for efficient performance from the contractor.
Flexibility: To provide for changes that could not be anticipated at the tender stage.
Risk sharing: To allocate all risks between the client and the contractor. The contractor will include a contingency in the tender to protect himself against unforeseen risks.

There are many reference publications, which review the various model forms of contract. There are also many lawyers and other members of the legal profession who make a good living from advising on contract types. The project engineer must steer a difficult path through the maze of contract law to determine what is the most appropriate contract route. In all cases, clear, unambiguous and well-defined scopes of work, project objectives and success criteria are essential base requirements.

Some hold the cynical view that the development of contract documentation is tedious and costly and adds no value. However, the very process of explaining and agreeing the key issues between the client and the contractor to enable a contract to be drafted is in itself a most valuable exercise. This process will lead to a better understanding of all the issues and help bring unresolved aspects to the attention of the project team early in the construction stage. The best contract documentation is well prepared, comprehensive in content and legally binding on both parties. Another highly desirable aspect is that the documents should never be used.

The project engineer will have updated the specification documents, confirmed the time-scale and agreed the contract conditions with the selected contractor. The project Quality Plan will lay down the communication plans and define the roles and responsibilities for all the extended project team.

20.3 Project Planning

Effective and rigorous planning is an essential prerequisite to the successful execution of any project. Fortunately, a number of aids are available to assist the project engineer in this respect. Two of the most commonly used are the Gantt chart and PERT (*P*rogram *E*valuation and *R*eview *T*echnique), alternatively known as CPM (*C*ritical *P*ath *M*ethod). The Gantt chart was developed by an industrial engineer Henry J. Gantt for production scheduling during World War I. It is essentially a bar chart,

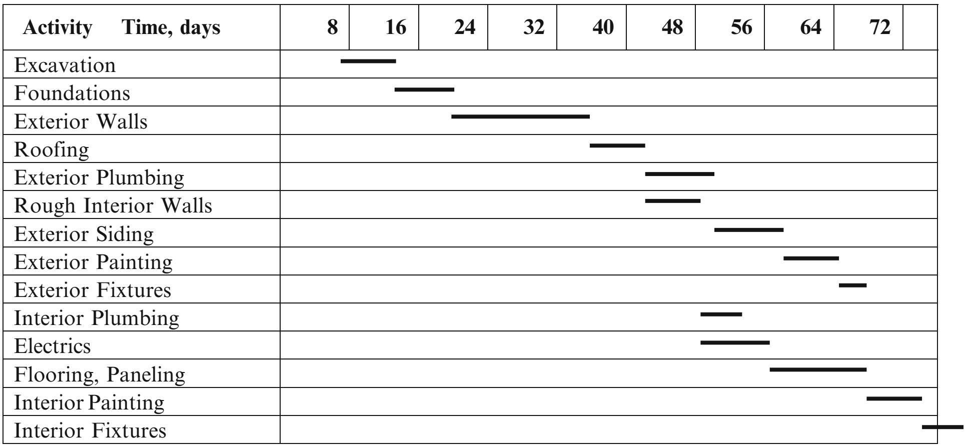


Fig. 20.2 Simplified Gantt Chart for construction project

which illustrates the duration and sequencing of the various activities involved in any project. Figure 20.2 represents a simplified Gantt chart for a hypothetical construction project. Gantt charts are simple and cheap to prepare and are easy to read, understand and update. They are ideal for small projects. Their main disadvantage is that they become cumbersome for large projects as the interrelation between the myriad of different activities becomes difficult to follow.

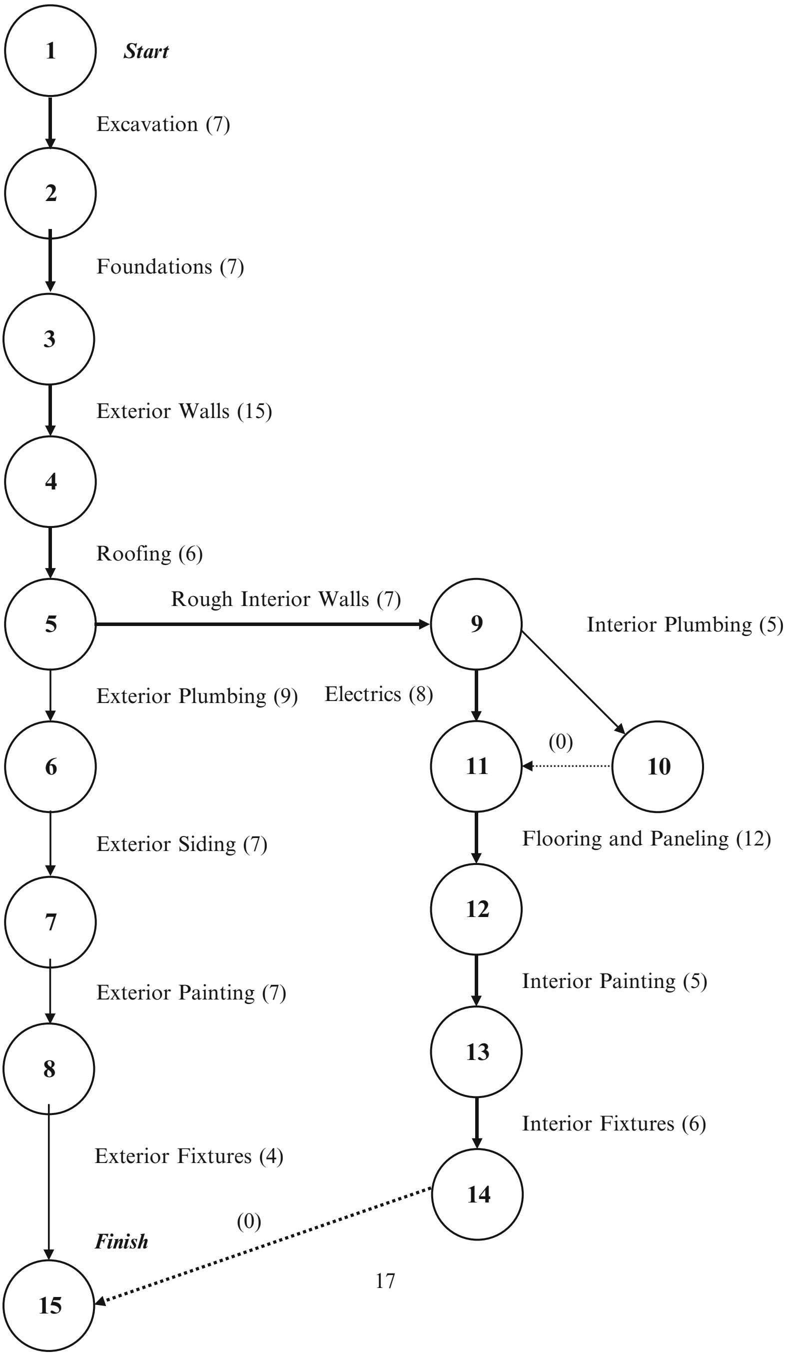
PERT (or CPM) diagrams are more suited to the planning and management of large-scale projects. In their basic form, they provide details of the sequencing and timescale of all project activities. They also identify those activities that lie on the so-called "critical path." These must be completed on schedule if the overall project timescale is to be met. In contrast, some delay can be accommodated in the case of noncritical activities. Figure 20.3 shows a PERT diagram for the same construction project as depicted in Fig. 20.2. The critical path is illustrated by the bold line, which shows that the project can be completed in a total of 73 days. In this case, a delay of 11 days can be tolerated in the noncritical activities $5 \rightarrow 6 \rightarrow 7 \rightarrow 8 \rightarrow 15$. In practice, most projects involve hundreds of activities and the construction of such charts manually is a long-drawn-out procedure. Fortunately, software packages (e.g., Microsoft Project) are available, which considerably simplify this task. These analyze not only the sequencing and timing of individual activities but also provide details of for example the manpower requirements and costs associated with each of these activities. The use of such programs enables a number of "what if" scenarios to be evaluated and gives rapid feedback on the effect of changing circumstances, such as delays in one or more project activities.

20.4 Approvals and Permits

Each country and region will have specific requirements that must be met. These requirements will apply both during construction and after hand-over of the completed facility. The construction aspects will be subject to Health and Safety guidelines, which will cover aspects such as drainage, ground works, scaffolding, etc.

The design must meet the local statutory requirements, which will define the style, size and materials of construction of the proposed facility. There will be regulations, which cover building design. The client's insurers should have an input into the final design to be sure that the proposals all meet the applicable Codes of Practice. The project engineer must ensure that the statutory obligations are understood and met by the members of the project team. There may be a need for regular

Fig. 20.3 Simplified PERT (CPM) diagram for construction project



inspections of the construction and these should be noted on the project program. Close interaction between the different parties is essential in order to ensure that no details are overlooked (see Figs. 20.4 and 20.5). It is the responsibility of the project engineer to ensure that this happens.

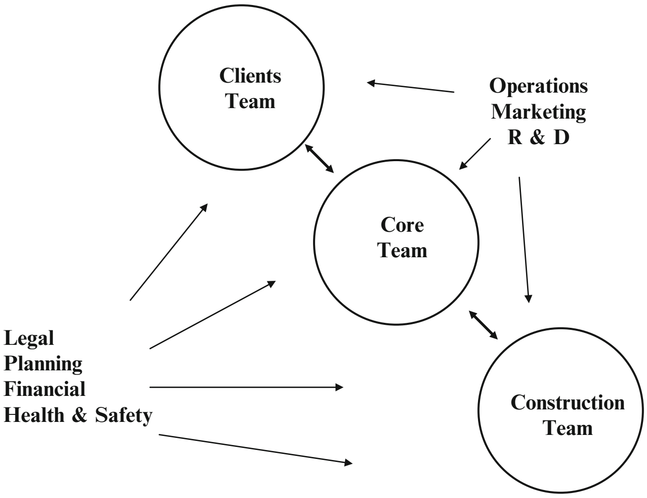


Fig. 20.4 The extended project team

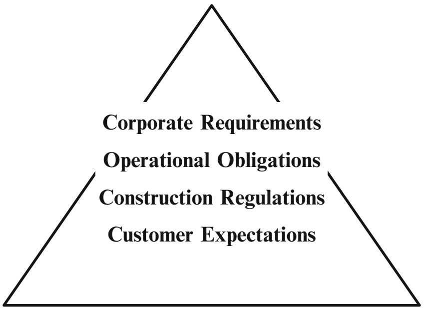


Fig. 20.5 The range of regulations

Once the project is approaching completion, specific areas may require progressive certification and sign-off before they are handed over to the client for use. The project engineer will need to liaise with the client's staff to ensure that this process runs smoothly.

The project engineer should keep an up-to-date record of all discussions and agreements reached on site, together with copy letters, certificates, etc. This will help in any discussions or disputes later in the project.

No project exists in a vacuum. The construction proceeds subject to the standards defined in the particular country. The operations must meet specific requirements before product is offered for sale.

20.5 Site Issues

Wherever possible a separate construction site should be established. This may be difficult where the development is taking place on an existing site. If the construction area can be securely fenced then the responsibilities for health and safety and public liabilities can be clearly defined as those of the main contractor.

The contractor should establish a sign-in and sign-out policy. The insurance of the site and control of access are also clearly the responsibility of the contractor. Periodic visits during the construction stage by senior staff, the future work-force and customers are to be encouraged. However, the laid-down procedures must be followed by all visitors to the site, including the most senior management.

The site should be as self-sufficient as possible with toilets, changing facilities, messing and rest areas being provided for construction workers. In addition, secure areas will be needed for materials storage. Car parking within the site may be difficult and specific areas may need to be designated. In rare cases, a remote facilities area will be the only option with a site shuttle bus to transfer workers to and from the construction areas.

If the construction site is adjacent to a food-production area, then great care should be exercised to avoid all risks of product contamination. Construction dust, tainting and foreign bodies are the most common sources of contamination. The construction areas need to be contained by solid partitions sealed to floors, walls and ceilings. Where possible a positive air pressure should be maintained in the production areas. Access routes for personnel in normal circumstances and also in emergencies need to be carefully thought through. The usual standards of housekeeping for a food-manufacturing site should be followed on the construction site. For example, there should be regular proofing against vermin, etc.

Supplies to the construction site should be arranged with the project engineer, who is responsible for off-loading, positioning and storage of the items. It should be noted that where proprietary equipment is purchased by the client for installation into the new facility, the responsibility for providing insurance against accidental damage, etc., after delivery rests with the client.

20.6 Construction

The primary responsibility of the project engineer in the construction stage is to ensure compliance with the agreed specification to meet the defined time-scale within the authorized cost plan. Regular project meetings should be arranged as defined in the quality plan. The project engineer will usually chair these meetings. One proven technique is to hold a brief update meeting with the client immediately after the project meeting (Fig. 20.6). This will provide the opportunity to bring the client up to date with progress and raise any issues promptly. Requests for variations can then be resolved quickly and efficiently, thereby avoiding any risks of delay.

Whilst the main focus of attention at this stage of the project will be on the construction, many other aspects need to be considered to ensure that the completed facilities come on-stream smoothly. These ancillary aspects, which relate to personnel matters, equipment commissioning, hygiene, utilities and logistics issues, are discussed below.

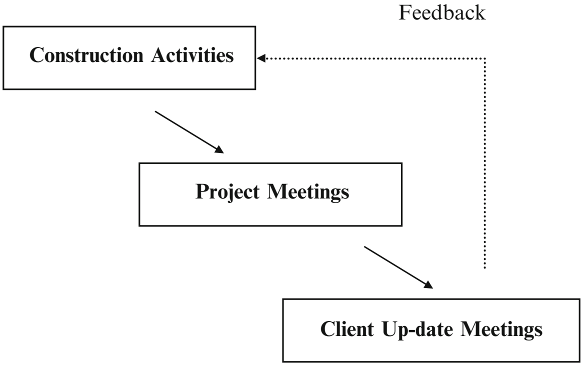


Fig. 20.6 Project meetings

Table 20.3 Ancillary items for start-up

- Equipment commissioning
- Materials for trial
- Recruitment and induction training
- Equipment training
- Catering facilities
- Laundry and work-wear provision
- Hygienic schedules
- Deep clean on handover
- Utilities availability
- Waste handling
- Approvals and certification

20.7 Ancillary Aspects

The success of the project will depend on meeting the criteria agreed at sanction. Any delay in start-up will cost money, either as a result of idle labor, missed markets, disappointed customers as well as capital depreciation with no additional income. If the project engineer can encourage the development of the ancillary aspects in parallel with the construction, this will encourage an efficient hand-over of the completed facility.

Many of the ancillary aspects will be handled by the client's management, but coordination across the functions will be helpful. If this role is assumed by the project engineer, it will ensure compatibility with the construction program. In particular, access of the client's personnel to the construction site for cleaning, IT commissioning, etc., will be facilitated.

Table 20.3 provides a checklist of typical items to be considered. It will be necessary to identify all the issues, which will need to be addressed in each particular situation. The project engineer should consider holding a workshop session with all interested parties to brainstorm all the potential issues that affect the start-up. The key issues can then be added to the construction program if necessary.

With the construction program and the hand-over/start-up program combined, the client up-date meetings should concentrate on operational aspects. The project engineer can now refer back to the original objectives of the project and structure the hand-over activities to demonstrate compliance and achievement of the agreed success criteria.

20.8 Completion

The final task involved in the completion and hand-over process is the compilation of a post-completion "snagging list." This will identify the incomplete items, any remedial works necessary to meet the standards, and alterations found necessary after commissioning.

The contract documents will define the procedures to be followed to rectify items that are incomplete or inadequate. The "defects liability" periods will be defined. The project engineer will need to manage the formal hand-over procedure and develop with the contractor the cost schedules for the final accounts.

When the dust has settled and the plant is in operation, the project engineer should convene a project critique to explore in a constructive manner those aspects of the project that could have been handled better. The purpose of this is not to blame anyone for shortcomings but rather to identify how project management could be improved.

. . .we can always do it better. . .

Further Reading

Barrie, D.S. and Paulson, B.C. (1991) “Professional construction management”, 3rd edit., McGraw-Hill, New York, 672 pp.

Halpin, D.W. and Senior, B.A. (2010) “Construction management”, John Wiley & Sons, Hoboken, NJ, 480 pp.

Fewings, P. and Jones, M. (2005) “Construction project management. An integrated approach”, Taylor & Francis, New York, 400 pp.

Kharbanda, O.P., Stalloworthy E.A. and Williams L.F. (1987) “Project cost control in action”, 22nd edit., Gower, Aldershot, UK, 320 pp.

Walker, A. (2007) “Project management in construction” John Wiley & Sons, Hoboken, NJ, 328 pp.

Index

C.G.J. Baker (ed.), *Handbook of Food Factory Design*, DOI 10.1007/978-1-4614-7450-0,