Chapter 1: Introduction to Process Integration

1.1 Process Integration

1.1.1 Introduction to Process Integration

Process integration represents an important branch of process engineering initiated in the late 1970's. It refers to the system-oriented, thermodynamics-based, integrated approaches to the analysis, synthesis and retrofit of process plants. The goals of process integration are 1) to integrate the use of materials and energy, and 2) to minimize the generation of emissions and wastes.

Process integration is built on three basic concepts:

1. Consider the big picture first by looking at the whole manufacturing process as an integrated system of interconnected processing units as well as process, utility and waste streams.

2. Apply process-engineering principles, such as thermodynamics and mass and energy balances, to key process steps to establish *a priori* the attainable performance targets on the use of materials and energy and the generation of emissions and wastes (e.g., the minimum utility consumptions, the minimum CO_2 and NO_x emission levels, the minimum freshwater requirement, etc.).

3. Finalize the details of process design and retrofit later to realize the established performance targets.

Figure 1.1 describes the relationships between the known branches of process integration. In general, we select from two approaches to an integrated process design. We apply *the pinch concept* for integrating energy (e.g., targeting heating- and cooling-utility consumptions) and mass (e.g., analyzing solvent-recovery systems or water-using operations), or *use a mathematical optimization approach* (e.g., minimizing effluent-treatment flowrates in a wastewater-treatment system).

How important is process-integration technology to chemical process design? According to one practicing engineer, “At the M.W. Kellogg Co., we firmly believe that process-integration technology is just good process design, and every process engineer should understand and know how to use these tools.” (Morgan, 1992) The front cover of the August 1994 issue of the official monthly publication of the American Institute of Chemical Engineers, *Chemical Engineering Progress*, features an important part of process-integration technology with its headline, “Knock Down Plant Inefficiencies with Pinch Analysis: Bottlenecks, Emissions, Energy and Capital Costs”. This same issue also includes a state-of-the-art overview of the field of pinch technology by Linnhoff (1994), who, along with his coworkers, has made important contributions to the field. Smith’s 1995 design text, *Chemical Process Design*, provides a good survey of process-integration technology (Smith, 1995a) and further underscores the importance of this methodology.

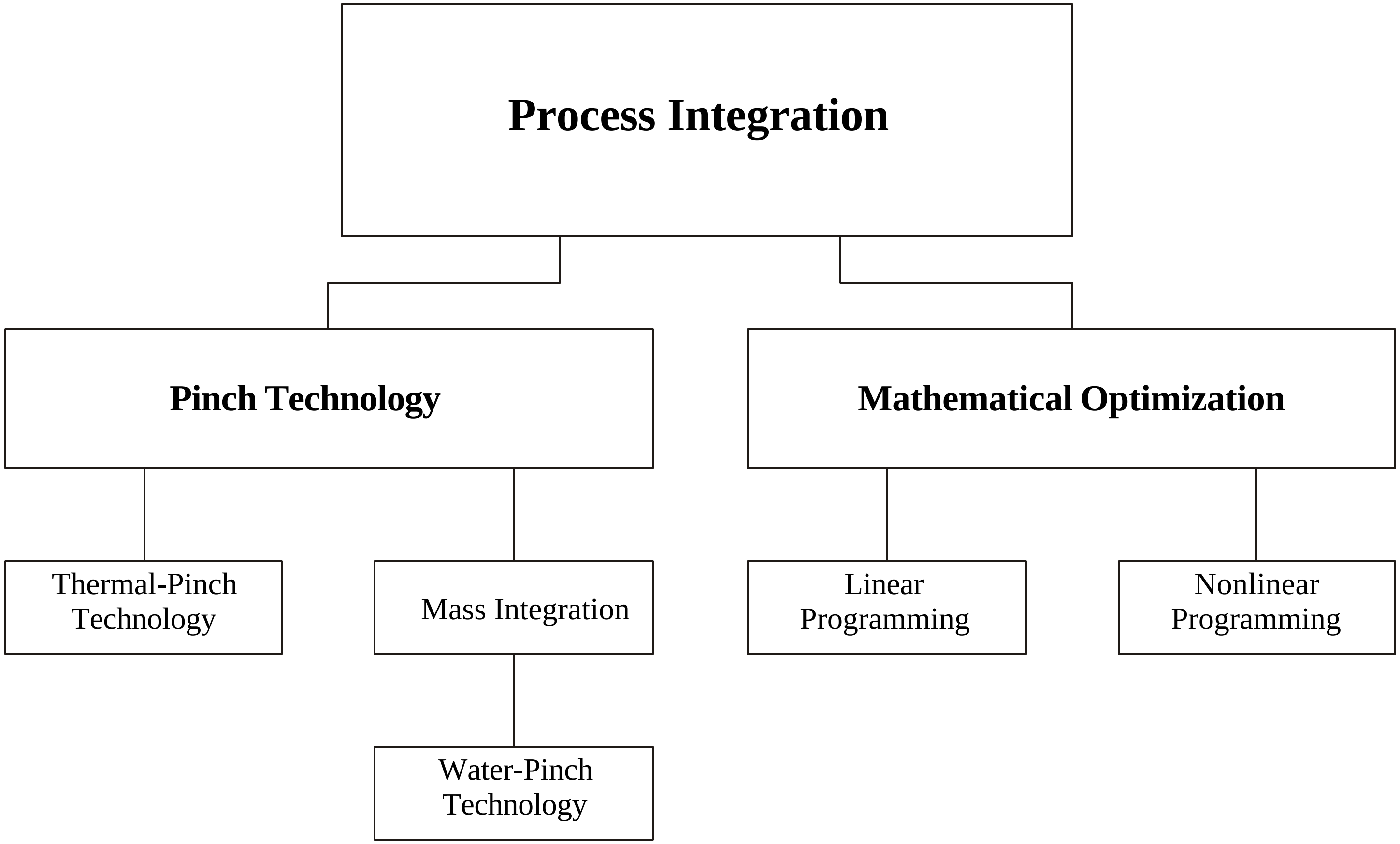

Figure 1.1. The tools of process integration.

1.1.2 Heat Integration through Pinch Technology

An important early development of process integration is *pinch technology for heat integration*. Here, the basic problem is to synthesize or retrofit a network of exchangers, heaters, and/or coolers to transfer the excess energy from a set of *hot streams* to a set of *cold streams*, or streams that require heating. Figure 1.2 illustrates a typical crude preheat-exchanger network around the topping tower in a petroleum refinery as designed without process-integration technology (Huang and Elshout, 1976). Exchangers, heaters and coolers are designated E, H and C, respectively, and four hot distillate-product streams (S_{h1}-S_{h4}) heat the cold crude oil S_{c1} before it enters the distillation column. Natural gas and cooling water serve as the heating-utility stream (S_{hu}) and cooling-utility stream (S_{cu}), respectively. We use process integration and pinch technology to *analyze* this system to minimize utility consumption and *synthesize* a heat-exchanger network and utility system to achieve this goal.

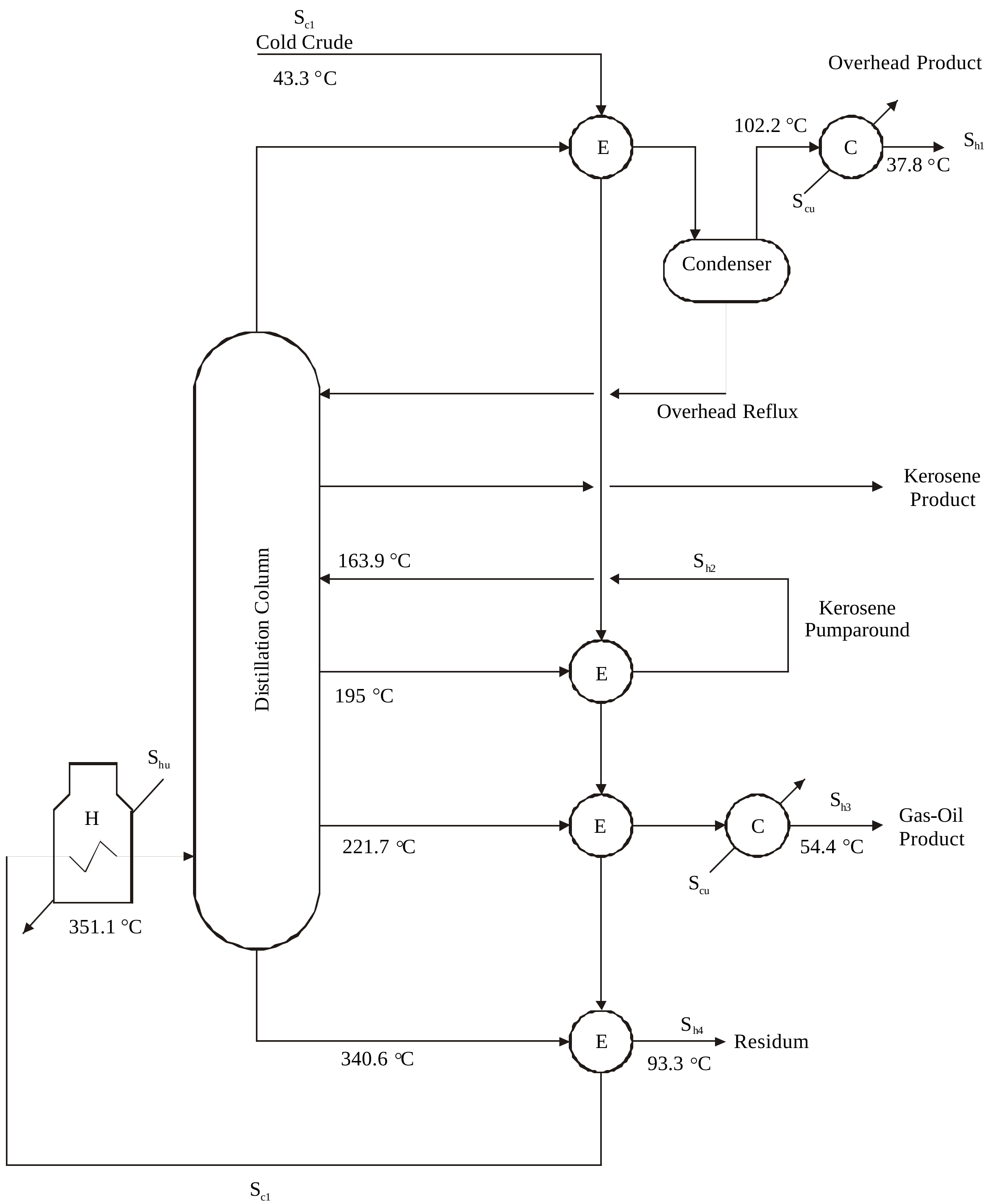

Figure 1.2. A typical heat-exchanger network for crude-preheat recovery (Huang and Elshout, 1976).

A key breakthrough in the design and retrofit of such networks is the identification of *the pinch-point temperature* (Umeda, et al., 1978; Linnhoff and Flower, 1978). By applying the principles of thermodynamics and energy balances to systematically analyze heat flow across various temperature levels throughout a manufacturing process, we can identify a temperature level, called the pinch point. Above this point, cooling utilities are unnecessary; below this point, heating utilities are unnecessary. In other words, it is more cost-effective to cool hot process streams above this temperature by using cold process streams than by using cooling utilities. Similarly, it is more cost-effective to heat cold process streams below this point by using hot process streams than by using heating utilities.

Significant developments in pinch technology for heat integration over the past fifteen years have enabled practicing engineers to establish *a prior* a number of attainable targets when designing new heat-exchanger networks, or retrofitting existing networks, including:

- the minimum number of equipment units (i.e., exchangers, heaters and coolers);
- the minimum investment cost of equipment units;
- the minimum operating costs of utilities (i.e., the minimum heating- and cooling-utility consumptions).

Pinch technology for heat integration is divided into three tasks:

1. *Analysis*. Identifying, *a priori*, the design targets, such as the minimum consumption of utilities (steam, cooling water and others), the minimum number of heat-exchange units (exchangers, heaters and/or coolers), the minimum surface area of heat-exchange units, etc..

2. *Synthesis*. Designing a heat-exchanger network that achieves the identified design targets.

3. *Retrofit*. Modify an existing process to maximize the use of process-to-process heat exchange and minimize the use of external utilities through effective process changes.

1.1.3 Mass Integration through Pinch Technology

A recent development in pinch technology that deals with pollution prevention, resource recovery, waste reduction, etc. is mass integration. El-Halwagi (1997), in his text, *Pollution Prevention through Process Integration - Systematic Design Tools*, gives the following definition: "*Mass integration* is a systematic methodology that provides a fundamental understanding of the global flow of mass within a manufacturing process and employs this holistic understanding in identifying performance targets and optimizing the generation and routing of species through the process." In short, a mass exchanger is any direct-contact, countercurrent mass-transfer unit that uses a mass-separating agent (MSA). Mass-exchange operations include absorption, adsorption, ion exchange, leaching, solvent extraction, stripping and similar processes, while mass-separating agents include solvents, adsorbents, ion-exchange resins and stripping agents. A review of the development and applications of mass-exchange networks between 1989 and 1997 appears in El-Halwagi (1997).

Figure 1.3 shows an example of a proposed mass-exchange network in the manufacturing of acrylonitrile (CH_3N, or AN) from the oxidation of ammonia (NH_3) and propylene (C_3H_6) (El-Halwagi, 1997).

A mass-exchange integration problem involves transferring mass from rich process streams (decreasing their concentrations) to lean process MSAs (increasing their concentrations at little operating cost) so that each stream reaches its desired outlet concentration, while minimizing waste production and utility consumption (including freshwater and external mass-separating agents). El-Halwagi and his coworkers have extended pinch technology to cover designing and retrofitting mass-exchange networks to achieve minimum flowrate targets on external utility streams (external MSAs).

Practicing engineers can answer several important questions when retrofitting existing facilities and designing new mass-exchange networks. These questions include:

- What are the maximum amounts of process MSAs that can be employed to remove contaminants from the contaminant-rich process streams with little operating costs?

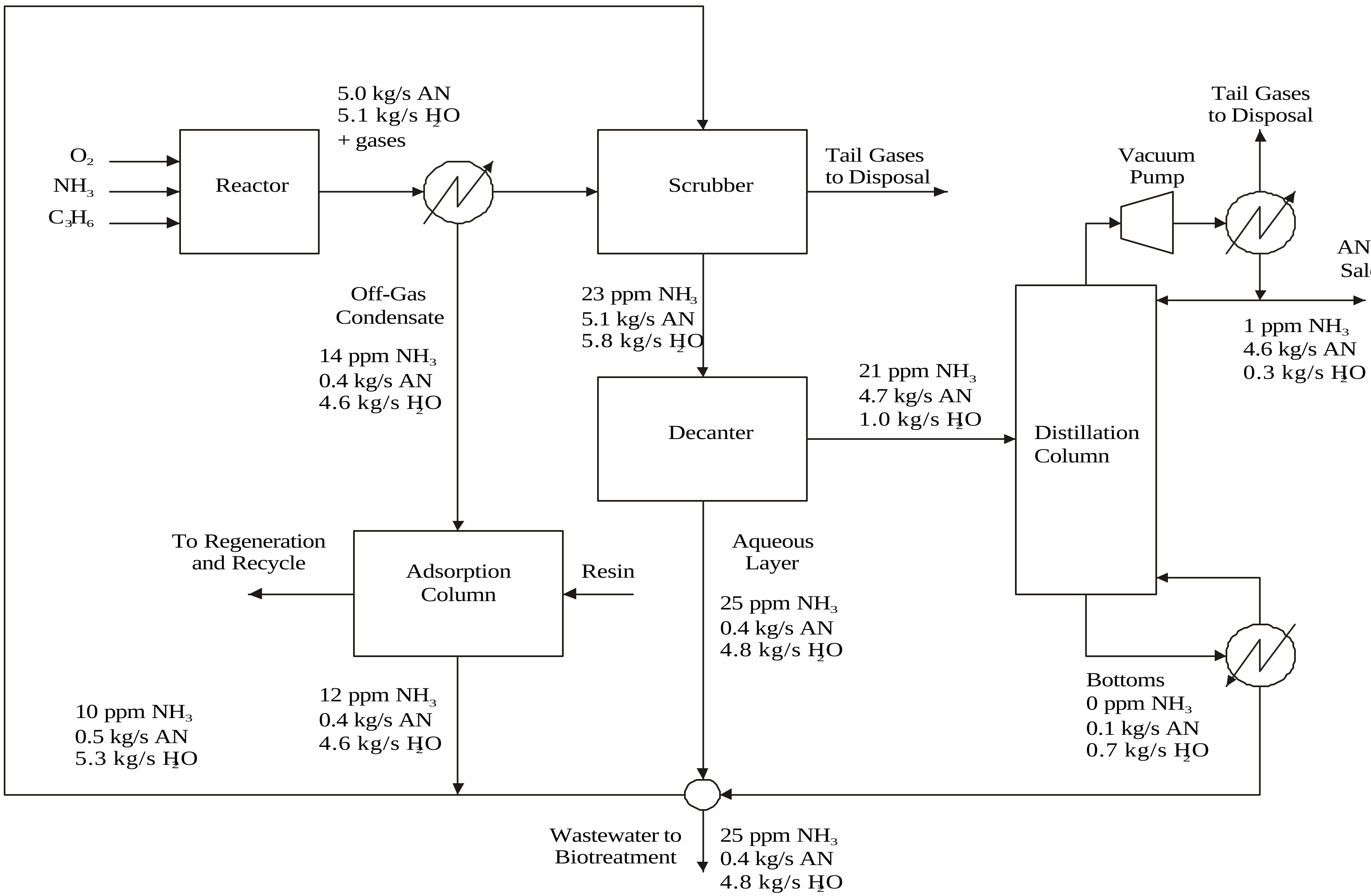

Figure 1.3. A proposed mass-exchange network in the manufacturing of acrylonitrile (C_3H_3N or AN) by oxidation of ammonia (NH_3) and propylene (C_3H_6). Reprinted with permission from *Pollution Prevention via Process Integration: Systematic Design Tools*, by M. M. El-Halwagi, Academic Press, Inc., San Diego, CA (1997).

- What are the minimum flowrates of external MSAs that are required to remove contaminants not extracted by process MSAs and in what order should multiple external MSAs be used?

- How do we design a new mass-exchange network, or retrofit an existing network, to meet these targets?

- How should we modify a manufacturing process to maximize the use of process MSAs and minimize the use of external MSAs?

Once again, to answer the preceding questions, we divide the technology into three tasks:

1. *Analysis*. Identifying, *a priori*, the maximum consumption of process MSAs and the minimum consumption of external MSAs.

2. *Synthesis*. Designing a mass-exchange network that achieves the identified flowrate targets for process and external MSAs.

3. *Retrofit*. Modifying an existing mass-exchange network to maximize the use of process MSAs and minimize the use of external MSAs through effective process changes.

As noted above, over the past fifteen years, pinch technology for heat integration has developed into a mature design methodology that has become standard engineering practice in designing and retrofitting process plants for energy conservation. In contrast, mass-exchange networks still suffer from some practical problems that hinder their real-world implementation, most notably, the inability to easily transfer mass from rich to lean streams because of the difficulty in choosing or developing the right mass-transfer equipment, and in identifying and selecting the appropriate mass-separating agents – if in fact the right equipment and/or separating agents exist (Sikdar and Hilaly, 1996).

1.1.4 Water-Pinch Technology for Industrial Water Reuse

Conceptually, water-pinch technology is a type of mass integration involving water-using operations; it does not, however, involve the same practical problems that hinder the real-world implementation of mass-exchange networks, simply because water-pinch technology represents an existing class of manufacturing operations.

Figure 1.4 illustrates a proposed water-using network for a specialty chemical plant. Here, the system involves complications like flowrate changes (i.e., water gains in the dewatering filters) and constraints (i.e., a fixed flowrate of water through the cyclone).

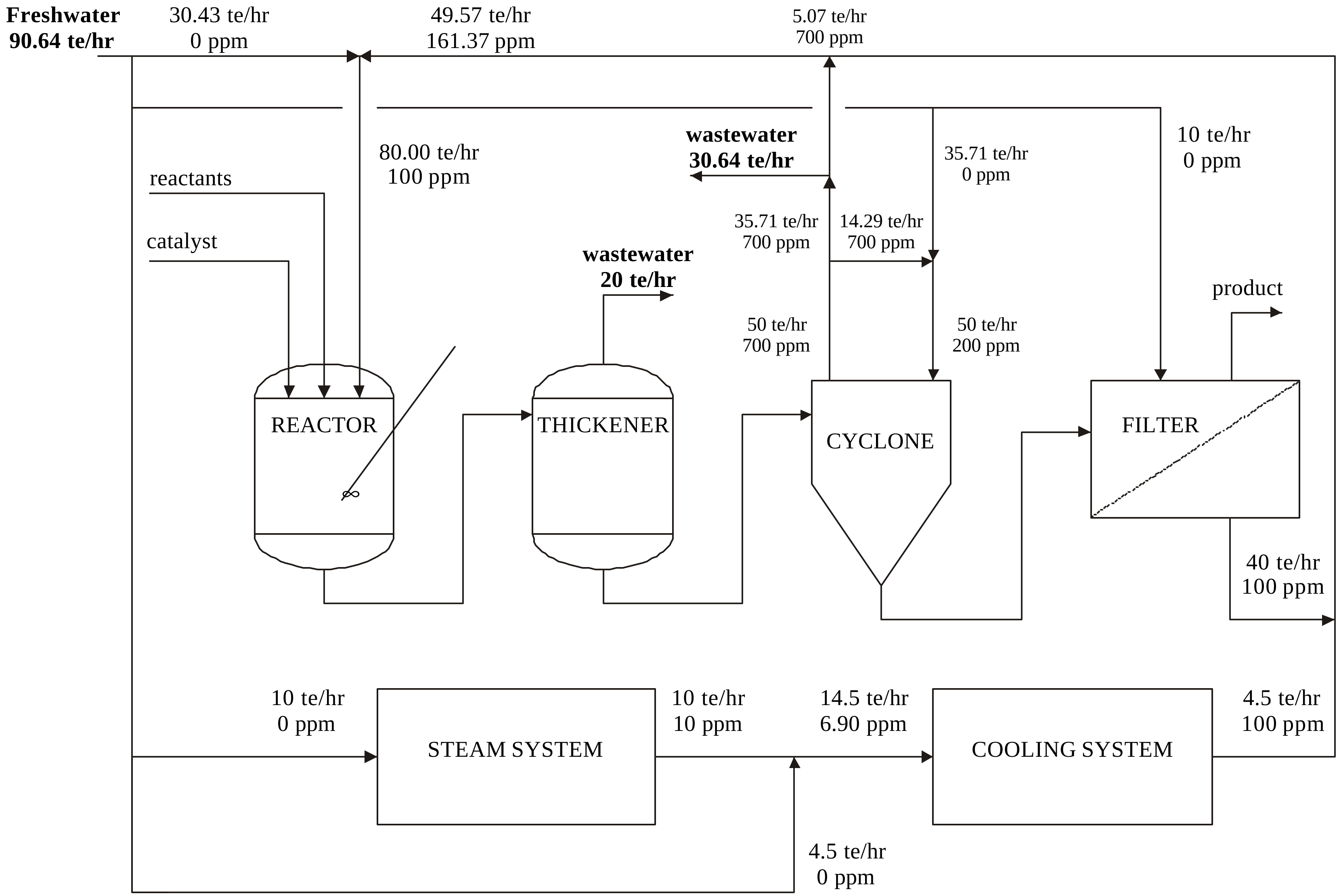

Figure 1.4. Proposed water-using network for a specialty chemical plant (Wang and Smith, 1995).

Water-pinch technology gives answers to a number of key questions when retrofitting existing facilities and designing new water-using networks in manufacturing processes. For water and effluent-treatment systems:

- What are the maximum water-reuse target and the minimum wastewater-generation target for a manufacturing process?
- How do we design a new water-using network, or retrofit an existing network, to meet these targets?
- What is the minimum treatment-flowrate target in an effluent-treatment system for a manufacturing process?
- How do we design a new effluent-treatment system, or retrofit an existing system, to achieve the minimum treatment flowrate?
- How should we modify a manufacturing process to maximize water reuse and minimize wastewater generation?

To answer the preceding questions, water-pinch technology is divided into three:

1. *Analysis*. Identifying, *a priori*, the minimum freshwater consumption and wastewater generation in water-using operations (*water-pinch analysis*)

2. *Synthesis*. Designing a water-using network that achieves the identified flowrate targets for freshwater and wastewater through water reuse, regeneration and recycle (*water-pinch synthesis*)

3. *Retrofit*. Modify an existing water-using network to maximize water reuse and minimize wastewater generation through effective process changes (*water-pinch retrofit*).

1.1.5 Process Integration through Mathematical Optimization

Mathematical optimization techniques are effective tools for minimizing an objective function (e.g., the total cost of freshwater consumption and wastewater treatment) subject to constraint relationships among the independent variables. *Linear programming* is a powerful tool capable of finding the minimum value of a linear objective function subject to linear constraints, while *nonlinear programming* is useful for minimizing a nonlinear objective function subject to nonlinear constraints.

Mathematical optimization has been applied to supplement the pinch concept. For example, complex heat-exchanger networks may be better designed by minimizing costs subject to the constraints governing the network design. Both linear and nonlinear programming techniques are adept at handling water-reuse and effluent-treatment problems. Here, large multiple-contaminant systems and water-using operations may not fit the pinch concept. In particular, we develop nonlinear models to represent regeneration processes, flowrate constraints (e.g., a fixed flowrate) and multiple contaminants. This dissertation also compares mathematical optimization techniques to pinch technology to help in selecting an appropriate solution technique.

1.2 Case Studies: Reducing Energy Costs and Minimizing Wastes

1.2.1 Heat Integration for Energy Efficiency

This section briefly discusses industrial-utility systems and gives examples of how heat integration can minimize utility consumption, wastewater generation and gaseous emissions.

1.2.1.1 Industrial-Utility Systems

Figure 1.5 illustrates a typical industrial-utility system featuring interconnected utilities. Here, heating utilities include several levels of steam and a fired furnace, while cooling utilities include cooling water and refrigeration. Complex interactions occur between individual utilities (e.g., steam turbines provide steam at lower pressures and generate shaft work and electricity to drive compressors in the refrigeration system).

The powerhouse contains steam boilers as well as steam turbines producing several steam levels. Chapter 6 of *Industrial Water Reuse and Wastewater Minimization* (Mann and Liu, 1999) contains details on steam-boiler design and operation.

Fired furnaces provide heating for processes that require high temperatures or heat loads. By optimally designing and integrating fired furnaces into the process, we can minimize fuel consumption and emissions.

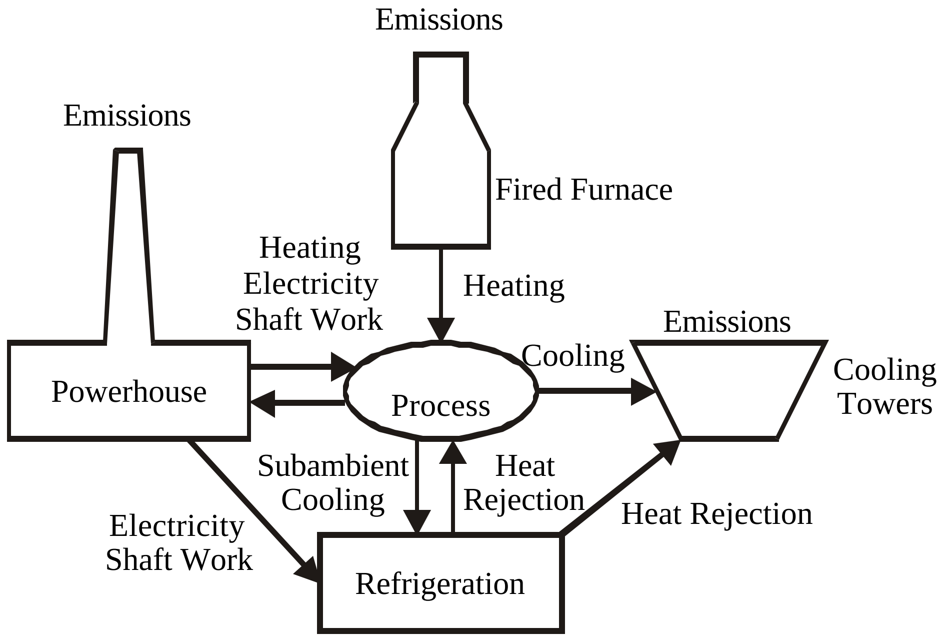

Figure 1.5. Typical industrial utility systems.

Cooling towers meet the majority of cooling demands of the process. Cooling takes place due to evaporation of cooling water to the atmosphere. Water-makeup and -blowdown streams maintain contaminant levels below acceptable levels – producing significant wastewater streams. Chapter 6 of *Industrial Water Reuse and Wastewater Minimization* (Mann and Liu, 1999) contains details on cooling-tower design and operation.

Refrigeration systems provide subambient cooling to the process. Shaft work to drive compressors is provided through electric drives and steam turbines. Heat is rejected to cooling water and the process. Chapter 6 discusses refrigeration systems and integration with the process.

1.2.1.2 Heat-integration in an Ethylene Plant.

This section presents the results of a heat-integration study of an ethylene plant first defined by Exxon Corporation (Fien and Liu, 1994). In particular, we apply the commercial software tool, Aspen Pinch, to analyze the problem through pinch technology, model the cascaded refrigeration system and suggest economic grassroots and retrofit designs.

The process consists of three general steps: 1) cracking and quenching, 2) preliminary gas fractionating and 3) compression and product separation. First, liquid naphtha and recycled ethane are cracked in a fired heater and immediately quenched to minimize undesired side reactions. After quenching, gasoline and heavier fractions are removed in a low-pressure gasoline fractionator. The compression, separation and purification of the remaining products and off-gases offers the greatest opportunities for both optimizing the process flowsheet and integrating the heat and power systems. In this variation, the gases are first compressed in a five-stage scheme, dehydrated in a zeolite drier and separated. Figure 1.6 describes the distillation sequence. In the figure, heat duties are shown in kW within boxes.

Analysis of the existing design shows a relatively high degree of heat integration. Grassroots designs for the refrigeration and heat-exchanger systems indicate the need for an economizer. However, retrofit projects require payback periods in excess of 6 years. Thus, these retrofits are not recommended.

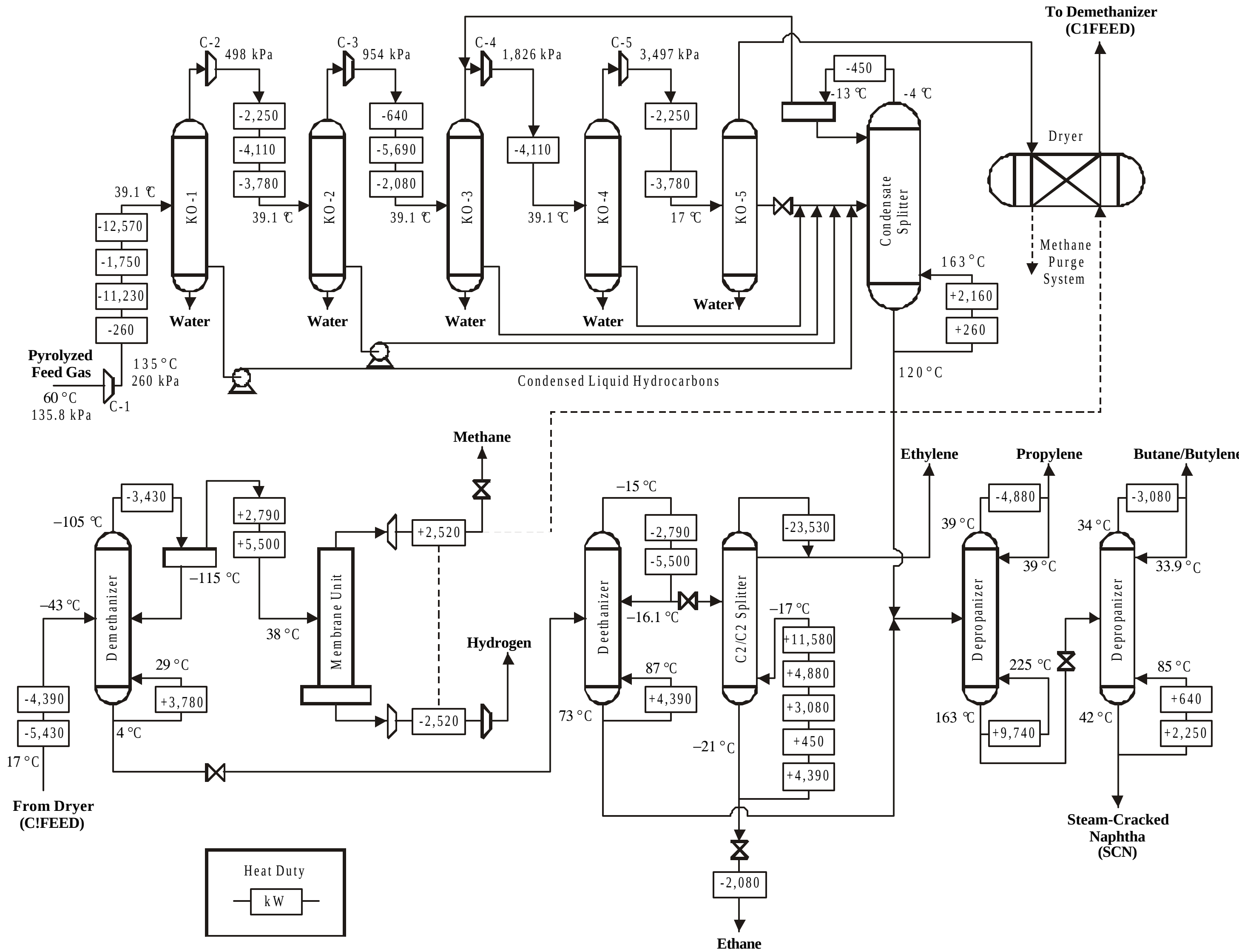

Figure 1.6. Ethylene plant before heat-integration study.

1.2.2 Industrial Mass-Exchange Operations

This section describes some categories of mass-exchange operations. Figure 1.7 illustrates six broad categories of industrial mass-exchange operations (El-Halwagi, 1997; McCabe, et. al, 1993):

Absorption involves the removal of contaminants from a vapor stream (process stream) with a liquid solvent (MSA). In Figure 1.7a, contaminants are transferred from the gas phase (entering at the bottom of the unit and exiting from the top) to the liquid solvent (entering at the top of the unit and exiting from the bottom). An industrial example of absorption is flue-gas desulfurization.

Adsorption uses a solid (MSA) to adsorb contaminants from gas and liquid streams (process streams). An example is pressure-swing adsorption as an alternative to cryogenic distillation. Here, nitrogen and other contaminants are selectively adsorbed from air (process stream) on to activated carbon (MSA). The pressure is swung to lower pressures and the contaminants are desorbed or purged to regenerate the bed. Figure 1.7b illustrates this example.

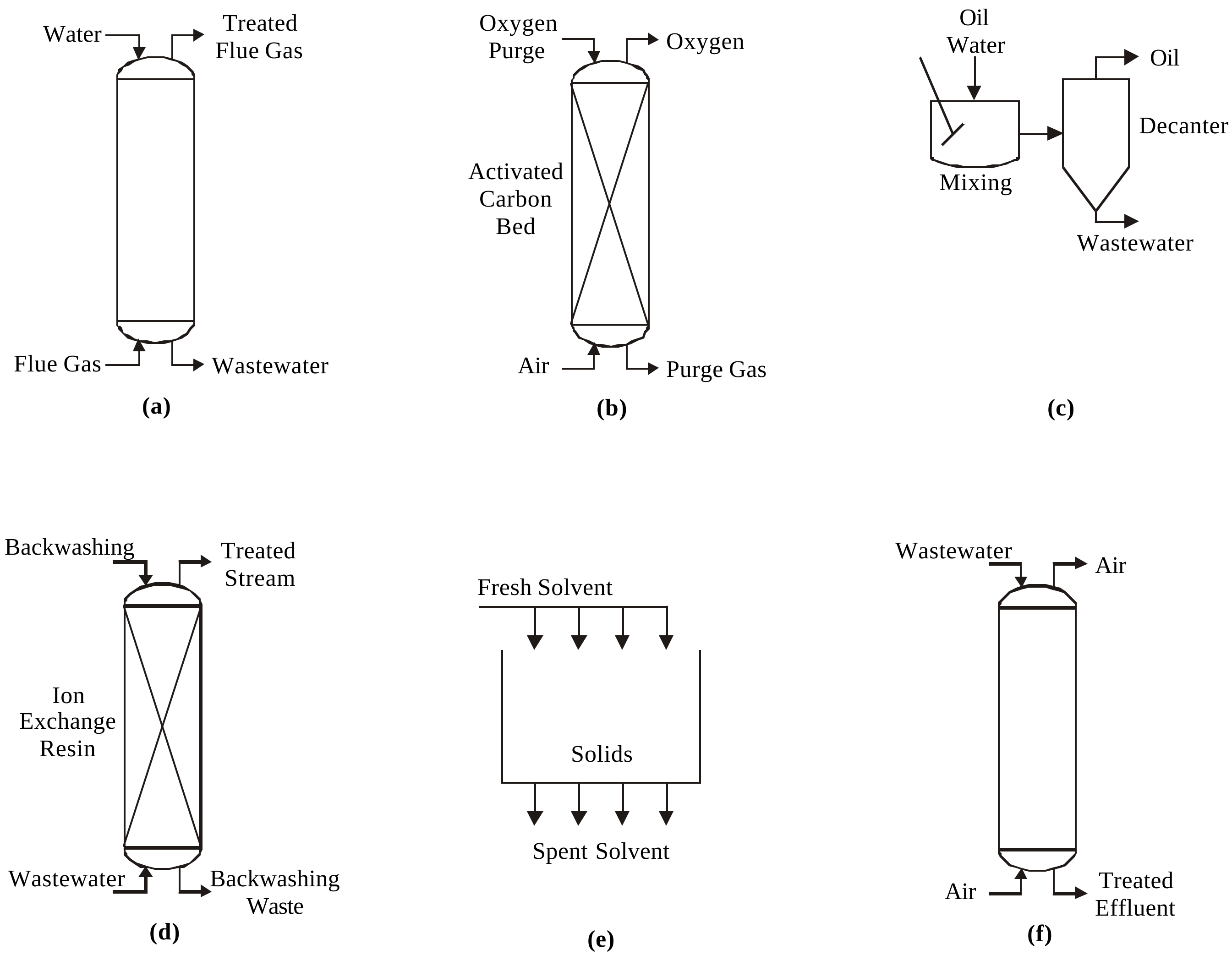

Figure 1.7. Examples of industrial mass-exchange operations: (a) absorption, (b) adsorption, (c) extraction, (d) ion exchange and (f) stripping.

Extraction is the transfer of contaminants from one liquid phase to another in a countercurrent contactor. Figure 1.7c shows two-liquid phases, oil (process stream) and water (MSA), contacted in a mixing unit and separated in a decanter. Industrial operations using extraction are numerous and include mixer-settlers (i.e., a desalter) and packed towers.

Ion exchange employs cation or anion resins (MSA) to replace ionic contaminant species in liquid streams (process stream). In many cases, we replace hazardous species with benign cation species like sodium and hydrogen or anion species like hydroxyl or chloride. Figure 1.7d illustrates a typical ion-exchange bed consisting of a vessel packed with an ion-exchange resin. The resin is regenerated through backwashing as the contaminant level in the product reaches a limiting concentration.

Leaching is the transfer of contaminants from a solid (process stream) to a liquid stream (MSA). Figure 1.7e illustrates leaching in a stationary bed. Here, solvent is sprayed over the solid material and recovered through a perforated bottom. Other industrial operations minimize solvent use through countercurrent contact between solid and solvent (i.e., moving-bed leaching).

Stripping is the transfer of contaminants from a liquid stream (process stream) to a gas stream (MSA). For example, we remove volatile organic compounds (VOCs) from wastewater streams through air or steam stripping. Figure 1.7f shows the liquid phase (e.g., a wastewater stream) descending through the column while the gas phase (e.g., air or steam as a MSA) passes countercurrently up the column.

1.2.3 Water-Pinch Technology for Industrial Water Reuse

This section describes industrial water uses and effluent treatment and then gives results from our own industrial case study of a petrochemical complex.

1.2.3.1 Typical Water Uses and Effluent-Treatment Systems

Figure 1.8 illustrates the most common water uses within a manufacturing facility in the process industries. Following preliminary water treatment, water is directed to *1) process uses, 2) utility uses* or *3) other uses*. The figure also illustrates common sources of wastewater, including process uses, condensate losses, boiler blowdown, and cooling-tower blowdown, wastewater from other uses such as housekeeping and storm-water runoff.

One common scheme for treating industrial wastewater streams is a distributed effluent-treatment system in which wastewater streams from different manufacturing processes require different treatment options. It can be more efficient and cost-effective to segregate these different wastewater streams and treat each of them separately rather than to combine these streams for common treatment in a centralized effluent-treatment system. Figure 1.9 contrasts these two types of effluent-treatment systems: centralized versus distributed. Chapter 4 of *Industrial Water Reuse and Wastewater Minimization* (Mann and Liu, 1999) focuses in more detail on designing distributed effluent-treatment systems to minimize the wastewater flowrate to be treated, thus minimizing overall treatment costs.

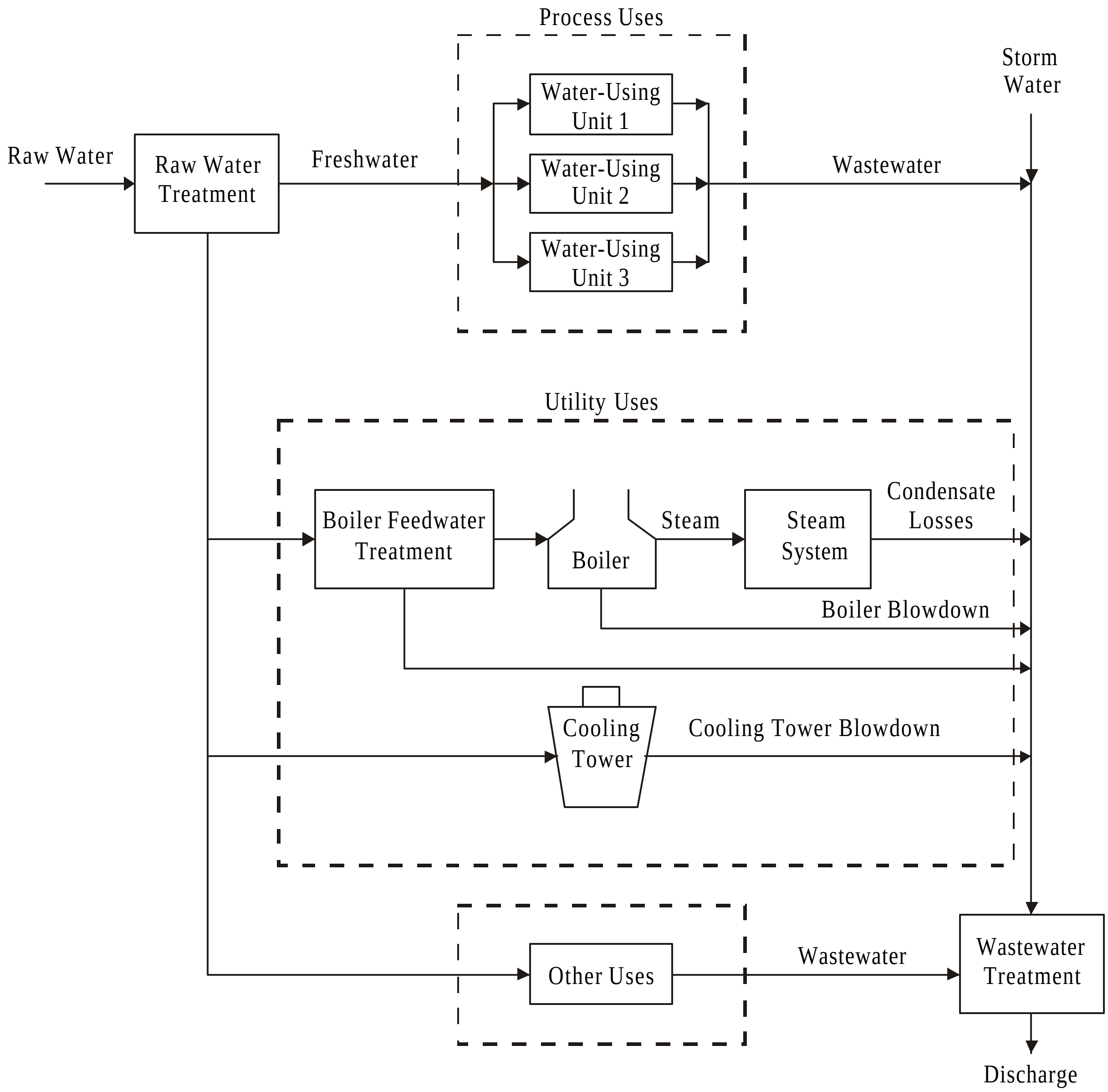

Figure 1.8. Typical water uses in the process industries: process uses, utility uses and other uses (Smith, 1995b).

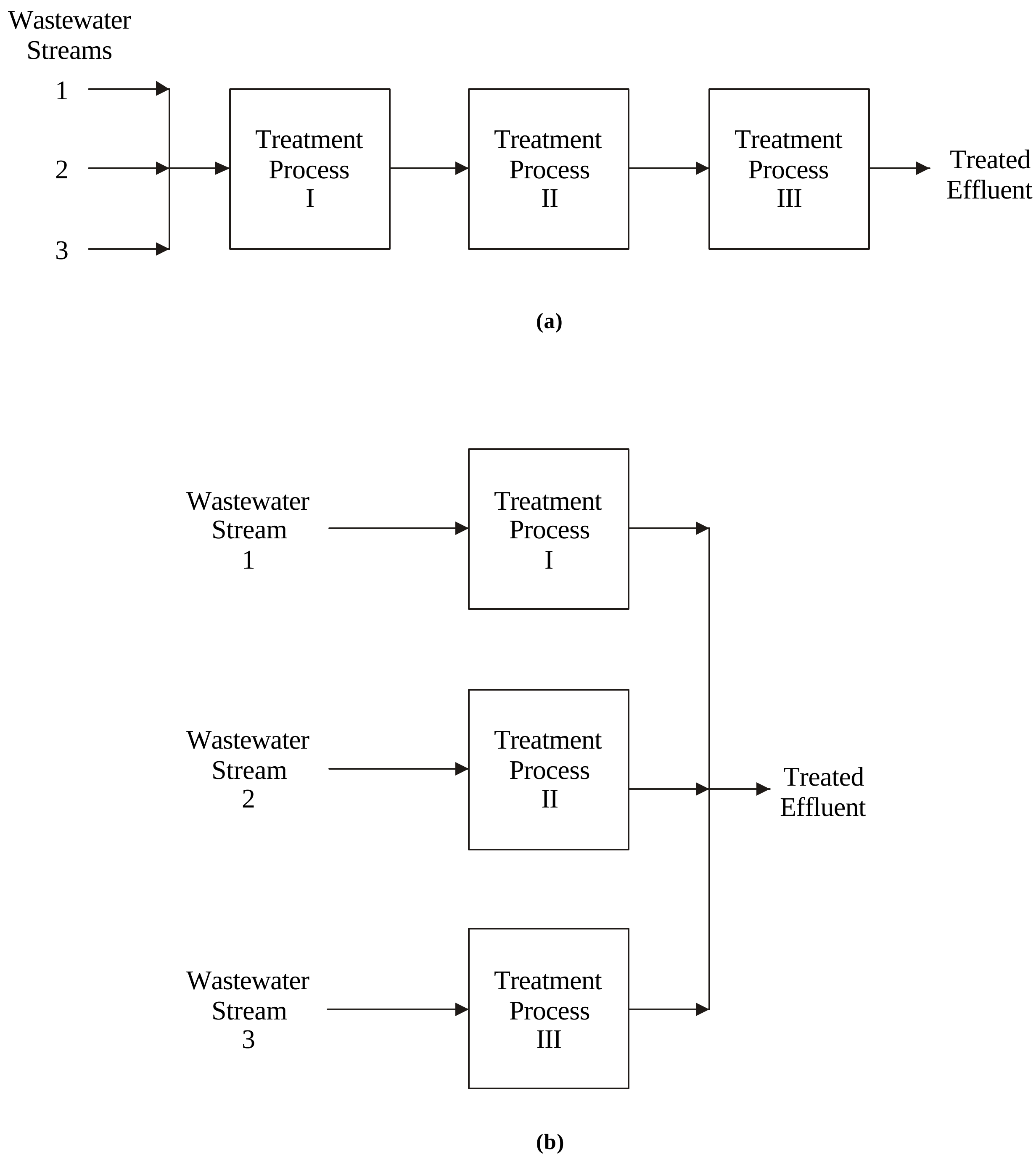

Figure 1.9. Illustration of (a) a centralized and (b) a distributed effluent-treatment system.

1.2.3.2 Water Reuse to Minimize Wastewater Generation in a Petrochemical Complex

Completed in 1996-97, this demonstration project was sponsored by the Water Resources Bureau, Ministry of Economic Affairs, Republic of China on Taiwan. The engineering firm, China Technical Consultants, Inc., Taipei, was in charge of all management and technical aspects of the project, working closely with the engineering and operational staff of the five manufacturing facilities. Our team at Virginia Tech introduced the concepts, provided the software, and shared the knowhow of water-pinch technology through training courses and project consultations held in Taiwan. In May 1997, a public briefing of the project results attracted over 160 practicing engineers and plant managers from across Taiwan's petrochemical industries.

Table 1.1 summarizes the project results, using pseudonyms for the plant names. Water-pinch technology, as indicated, could increase the average water reuse from 18.6% to 37.0%.

The first step in any water-reuse project is a comprehensive audit of water uses within a facility. Figure 1.10 illustrates the water uses at XX Petrochemicals, one of the five manufacturing facilities in the petrochemical complex, before applying water-pinch technology. Water use is distributed among the three categories: process, utility and other uses. The seven water-using operations in bold represent those considered for water reuse.

Table 1.1. Summary of the results from a water-reuse demonstration project in a petrochemical complex in Taiwan, 1996-97.

	Current Water Reuse		**Additional Project Water Reuse**		**Project Payback (Freshwater Savings)**	**Project Payback (Wastewater Treatment)**	**Total Water Reuse**
Plant	(te/day)	(%)	(te/day)	(%)	($/yr)	($/yr)	(%)
1. XX Petrochemicals	0	0	1082	19.9	152,000	105,800	19.9
2. XA Synthetic Fibers	720	18.3	1,398	35.6	196,000	136,700	53.9
3. XB Rubber and Plastics	1,578	26.3	295	4.9	41,500	28,900	31.2
4. XC Polymers	985	53.1	409	22.1	57,500	40,000	75.2
5. XD Petrochemicals	50	25.0	110	55.0	15,500	10,700	80.2
Total	**3,333**	**18.6 (average)**	**3,294**	**18.4**	**462,500**	**322,100**	**37.0 (average)**

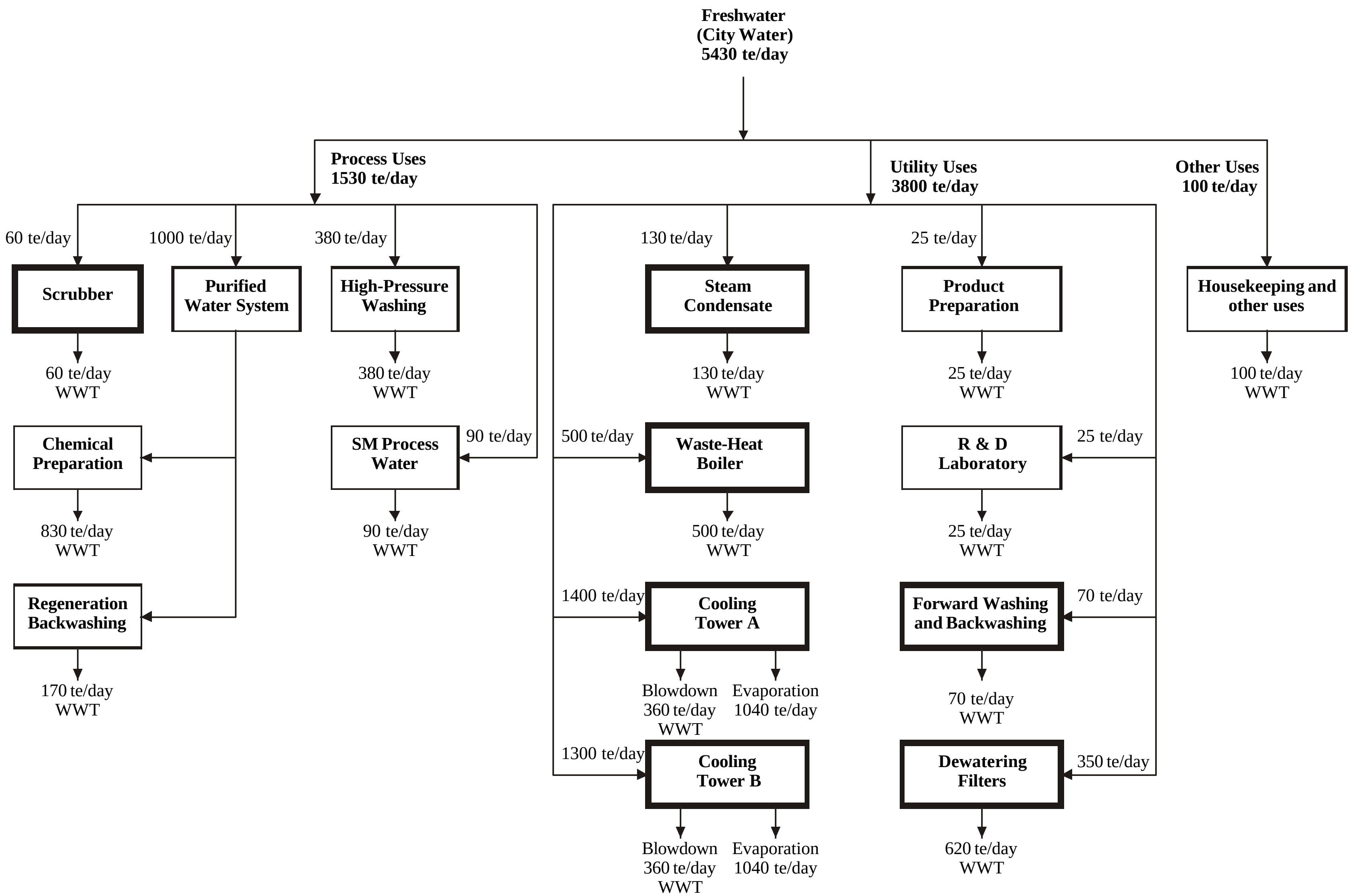

Figure 1.10. A water balance for XX Petrochemicals prior to applying water-pinch technology. WWT stands for wastewater treatment.

Table 1.2 summarizes the results of applying water-pinch technology to this facility: Freshwater consumption decreased by 1082 te/day; this decrease combined with the savings in wastewater treatment and disposal costs, yields an annual benefit of $292,200 per year for just over $50,000 in capital costs. Thus, *none* of the reuse options implemented requires a payback period of over 10 months.

Chapter 7 of *Industrial Water Reuse and Wastewater Minimization* (Mann and Liu, 1999) provides a more detailed look at this facility and explains how to apply water-pinch technology to the petrochemical complex.

Table 1.2. Cost/benefit analysis of the water-reuse options for XX Petrochemicals (in 1996 dollars).

Option	Water-Reuse	Needed Equipment (Retrofit)	Capital Investment ($)	Water Savings (te/day)	Annual Benefit ($/yr)	Payback Time (months)
1	Forward washing (FW) water as cooling tower A (CTA) makeup water	Buffer vessel pump, piping	6,550	42	11,340	7
2	Cooling tower B (CTB) blowdown reused as washing water for dewatering filters (DW)	Piping, control valves, small filter	1000	340	91,800	0.13
3	Effluent form the new RO (reverse osmosis) water-purification system reused as scrubber (SC) makeup water	piping	1,200	60	16,200	0.9
4	Cooling tower A (CTA) blowdown as cooling tower B makeup water	Existing piping	0	360	97,260	0
5	Boiler blowdown reused as cooling tower A (CTA) makeup water	Pump, heat exchanger, control valves, piping	43,640	195	52,650	10
6	Steam condensate reused as boiler feedwater	Existing piping	0	65	17,550	0
7	Cooling tower B (CTB) blowdown reused as reactor/filter washing water	piping	1,200	10	2,700	5.3
	Summary		**53,590**	**1082 te/day**	**292,200**	**<10 Months**

1.3 Dissertation Organization

1.3.1 Motivation and Goal of the Research

The goal of this research is to develop a unifying and practical approach to process integration applied to energy conservation, resource recovery, pollution prevention and waste minimization. Traditionally, the developers of process integration have been reluctant to acknowledge the relationships among its many branches. Figure 1.1 illustrated the relationships between the tools of process integration (i.e., pinch technology and mathematical optimization). In the following chapters, we develop a unifying approach to process integration through pinch technology and mathematical optimization. We complete the conceptual developments to unify the known branches of process integration, such as heat and mass integration, and wastewater minimization, and explore new frontiers of applications. We fully investigate the similarities and differences between pinch technology and mathematical optimization, and identify the best approach for a specific application. In addition, we develop PC-based, user-friendly software for implementing the unifying concepts in process integration, and evaluate the merits of advanced commercial software tools for process integration (e.g., Aspen Pinch) for applications to real industrial problems.

1.3.2 Research Tasks and Significance

This research involves the following tasks.

1. To fully develop the known branches of process integration including pinch technology and mathematical optimization. In particular, we concentrate on the development of water-pinch technology and mathematical optimization for analyzing and designing water-using networks and effluent-treatment systems.

2. To present the tools of process integration in a unified manner. By doing so, we discover new applications and limitations of these tools across the branches of process integration.

3. To develop new industrial applications of process integration and software tools to implement the technologies. Through computer automation, chemical, civil and environmental engineers can apply the tools of process integration effectively without the need for extensive training.

1.3.3 Significance of the Research

Until this time, no publication has presented details on the relationships among the applications of pinch technology. This dissertation contains an extensive guide to pinch technology applied to heat integration (e.g., energy conservation), mass integration (e.g., solvent-recovery systems) and water-pinch technology (e.g., water-using operations and effluent-treatment systems) in a unified manner that emphasizes the similarities and difference among various applications.

1.3.4 Dissertation Organization

Figure 1.11 illustrates the layout of this dissertation.

Chapters 2 through 7 give an extensive review of and present new tools for heat integration through pinch technology.

Chapter 8 discusses pinch technology for mass integration and introduce innovative tools for analyzing mass-exchange networks.

Chapter 9 and our text *Industrial Water Reuse and Wastewater Minimization* (Mann and Liu, 1999) give a complete guide to industrial water reuse and effluent-treatment system design.

Our text *Industrial Water Reuse and Wastewater Minimization* (Mann and Liu, 1999) introduces mathematical optimization and presents several examples of industrial applications. Chapter 10 presents emerging applications of mathematical optimization that expand the class of problems we can solve through mathematical optimization.

Chapter 10 also points out key similarities between the branches of pinch technology and mathematical optimization. We also include a guide to selecting an appropriate solution method (i.e., pinch technology or mathematical optimization) for process-integration problems.

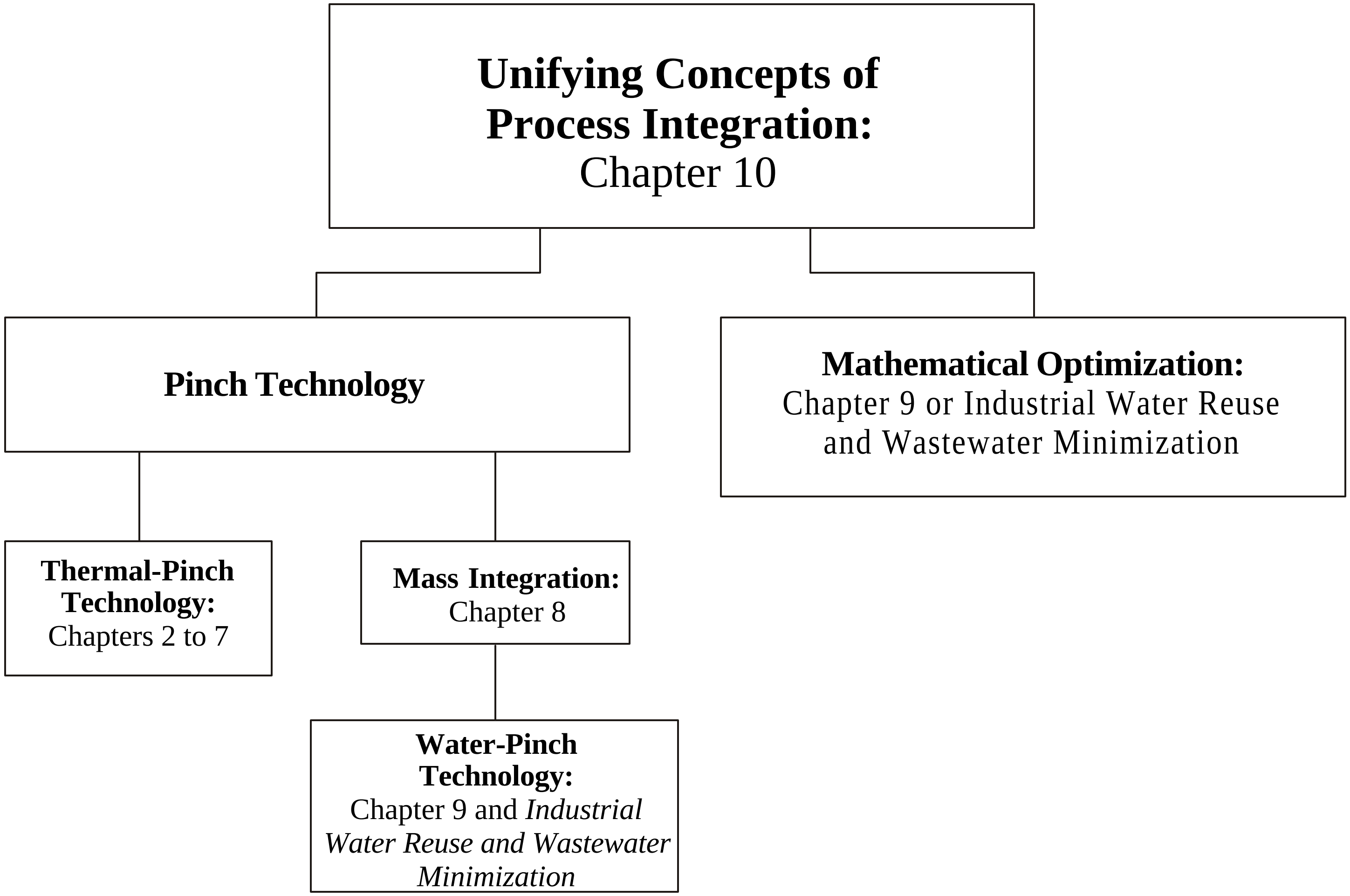

Figure 1.11. Dissertation layout.

1.4 Summary

- Process integration represents an important branch of process engineering initiated in the late 1970's. The goals of process integration are 1) to integrate the use of materials and energy, and 2) to minimize the generation of emissions and wastes.

- We divide process integration into two broad categories. The first, pinch technology was developed in the 1970s to integrate the use of energy in manufacturing. It was broadened in the 1990s to include pinch technology for mass integration and water-pinch technology. The second, mathematical optimization first evolved to solve simple linear problems and was later expanded to encompass many types of complex nonlinear problems.

- A heat-integration problem analyzes energy flows in a manufacturing process and identifies the minimum utility requirements to cool hot streams (decreasing their temperature) and heat cold streams (increasing their temperature).

- A mass-integration problem involves transferring mass from rich process streams (decreasing their concentrations) to lean process MSAs (increasing their concentrations at little operating cost) so that each stream reaches its desired outlet concentration, while minimizing waste production and utility consumption (including freshwater and external mass-separating agents).

- Pinch technology for heat integration has developed into a mature design methodology that has become standard engineering practice in designing and retrofitting process plants for energy conservation. In contrast, mass-exchange networks still suffer from some practical problems that hinder their real-world implementation, most notably, the inability to easily transfer mass from rich to lean streams because of the difficulty in choosing or developing the right mass-transfer equipment, and in identifying and selecting the appropriate mass-separating agents – if, in fact, the right equipment and/or separating agents exist (Sikdar and Hilaly, 1996).

- Water-pinch technology evolved from mass integration but does not suffer from the same problems that hinder its implementation. Instead, the technology analyzes an existing set of operations to maximize water reuse and minimize effluent treatment.

- A unified approach to process integration is needed to develop the technology to its maximum extent. Here, we consider tools from each branch of the technology and develop new techniques for process integration.

References

Autret, E., "Studies in Process Integration of Energy and Environmental Systems," Chapter 5, pp. 329-408, "Application of Process Integration to Wastewater Minimization and the Design of Distributed Effluent Treatment Systems: Tutorial Examples," M.S. thesis, Virginia Tech, Blacksburg, VA, June (1995).

AWWA Research Foundation, *Water Reuse Needs Assessment*, prepared by CH2MHill, Inc., American Water Works Association, Denver, CO, Sept. (1988).

Belhateche, D. H., "Choose Appropriate Wastewater Treatment Technologies," *Chem. Eng. Prog.*, 91, No. 8, 32, Aug. (1995).

Buehner, F. W. and J. D. Kumana, "Fresh Water and Wastewater Minimization: Concepts, Software and Results," *Chemputers IV Conference*, Houston, TX, March (1996).

Buehner, F. W. and A. P. Rossiter, "Minimize Waste by Managing Process Design," *Chemtech*, 26, No. 4, 64, April (1996).

Byers, W., "Zero Discharge: A Systematic Approach to Water Reuse," *Chem. Eng.*, 102, No. 7, 96, July (1995).

Byers, W., W. Doerr, R. Krishnan and D. Peters, *How to Implement Industrial Water Reuse: A Systematic Approach*, Center for Waste Reduction Technologies (CWRT), American Institute of Chemical Engineers (AIChE), New York (1995).

Coetzer, D., C. Stanley and J. Kumana, “Systematic Reduction of Industrial Water Use and Wastewater Generation”, *AIChE National Meeting*, Houston, TX, March (1997).

Crook, J., D. A. Okun and A. B. Pincince (Camp Dresser & McKee, Inc.), *Water Reuse*, an assessment report, project 92-WRE-1, Water Environment Research Foundation, Alexandria, VA (1994).

DeSilva, F., “Tips for Process Water Purification”, *Chem. Eng.*, p. 72, Aug. (1996).

Dhole, V. R., “Fluid Efficiency”’ U.S. Patent 5,824,888, Oct. 20 (1998).

Dhole, V. R., N. Ramchandani, R. A. Tainsh and M. Wasilewski, “Make Your Process Water Pay for Itself,” *Chem. Eng.*, p. 100, January (1996).

Donovan, J. F. and J. E. Bates, *Guidelines for Water Reuse*, EPA-600/8-80-036, U.S. Environmental Protection Agency, Cincinnati, OH (1980).

Doyle, S. J. and R. Smith, “Targeting Water Reuse with Multiple Contaminants”, *Trans. IChem. E.*, 75, Part B, 181 (1997).

Eastman, A. R., R. A. Tainsh and G. J. Fien, “Minimizing Water Emissions Using WaterPinch Analysis”, *The Conference on Management Strategies for the Treatment and Reuse of Industrial Wastewaters*, University of Leeds, Leeds, United Kingdom, Jan. (1998).

Eckenfelder, W. W., Jr., *Industrial Water Pollution Control*, 2nd edition, McGraw-Hill, New York (1989).

El-Halwagi, M. M., *Pollution Prevention Through Process Integration: Systematic Design Tools*, Academic Press, San Diego, CA (1997).

El-Halwagi, M. M. and H. D. Spriggs, “Solve Design Puzzles with Mass Integration”, *Chem. Eng. Prog.*, 94, No. 8, 25, Aug. (1998).

Fien, Gert-Jan A. F. and Y. A. Liu, “Process Integration of an Ethylene Plant”, CACHE Process Design Case Studies, Vol. 7, July (1994).

Galan, B. and I. E. Grossmann, “Optimal Design of Distributed Wastewater Treatment Networks”, *Ind. Eng. Chem. Res.*, 37, 4036 (1998).

Goldblatt, M. E., K. S. Eble and J. E. Feathers, “Zero Discharge: What, Why and How,” *Chem. Eng. Prog.*, 89, No. 4, 22-27, April (1993).

Hamilton, R. and D. Dawson, "Pinch Cleans Up," *The Chemical Engineer*, p. 42, May 26 (1994).

Huang, F. and R. Elshout, "Optimizing the Heat Recovery of Crude Units," *Chem. Eng. Prog.*, 72, No. 7, 64 (1976).

Kemmer, F. N., editor, *The Nalco Water Handbook*, 2nd edition, McGraw-Hill, New York (1988).

Kuo, W. C. and R. Smith, "Effluent Treatment System Design", *Chem. Eng. Sci.*, 52, 4273 (1997).

Kuo, W. C. and R. Smith, "Designing for the Interactions between Water-Use and Effluent Treatment", *Trans. IChem E.*, 76, Part A, 287 (1998).

Kumana, J. D., "Water Conservation and Wastewater Minimization through Process Integration", *5th World Congress of Chemical Engineering*, San Diego, CA, July (1996).

Linnhoff, B. and J. R. Flower, "Synthesis of Heat Exchanger Networks. Part I. Systematic Generation of Energy Optimal Networks," *AIChE J.*, 24, 663 (1978).

Linnhoff, B., Townsend, D. W., Boland, D., et al., "A User Guide to Process Integration for the Efficient Use of Energy," *IChemE UK* (1982).

Linnhoff, B. and D. R. Vredeveld, “Pinch Technology has Come of Age,” *Chem. Eng. Prog.*, 80 No. 7, 33 (1984).

Linnhoff, B., “Use Pinch Analysis to Knock Down Capital Costs and Emissions,” *Chem. Eng. Prog.*, 90, No. 8, 32, Aug. (1994).

Linnhoff, B. and S. G. Hall, “Targeting for Furnace Systems Using Pinch Analysis,”

Liu, Y. A., “Process Synthesis: Some Simple and Practical Developments,” in *Recent Developments in Chemical Process and Plant Design*, pp. 147-260, Y. A. Liu, H. A. McGee, Jr. and W. R. Epperly, editors, Wiley, New York (1987).

Mann, J. G. and Y. A. Liu, *Industrial Water Reuse and Wastewater Minimization*, McGraw-Hill, New York (1999).

Metcalf and Eddy, Inc., *Wastewater Engineering: Treatment, Disposal and Reuse*, 3rd edition, revised by G. Tehobanoglous and F. L. Burton, McGraw-Hill, New York (1991).

Middlelebrooks, E. J., editor, *Water Reuse*, Ann Arbor Science Publishers, Ann Arbor, MI (1982).

Ministry of Economic Affairs, Water Resources Bureau, Republic of China, and China Technical Consultants, Inc., Energy Technical Services Center, Taipei, *Proceedings of the Public*

Briefing from Water-Savings Demonstration Project, Petrochemical Industry Complex, Kaohsiung, Taiwan, May (1997).

Montgomery, J.M., *Industrial Water Reuse: Cost Analysis and Pricing Strategies*, Office of Water Research and Technology, Washington, D.C., National Technical Information Service, PB81-215600, Arlington, VA, April (1981).

Moore, S., “Pinch Technology: It’s Not Just for Energy Anymore,” *Chem. Eng.*, 102, No. 8, 47, Aug. (1995).

Morgan, S. M., “Use Process Integration to Improve Process Design and the Design Process,” *Chem. Eng. Prog.*, 88, No. 9, 62 (1992).

National Research Council, *Quality Criteria for Water Reuse*, National Academy Press, Washington, D.C. (1982).

Nelson, K. E., “Process Modifications That Save Energy, Improve Yields, and Reduce Waste,” in *Waste Minimization through Process Design*, A.P. Rossiter, editor, pp. 119-132, McGraw-Hill, New York (1995).

Newton, D. and G. Solt, editors, *Water Use and Reuse*, Institution of Chemical Engineers, Rugby, Warwickshire, United Kingdom (1994).

Oleson, S. G. and G. T. Polley, "A Simple Methodology for the Design of Water Networks Handling Single Contaminants," *Trans. Inst. Chem. Eng.*, 75, Part A, 420 (1997).

Osantowski, R. A., J. C. Liello and C. S. Applegate, "Generic Pollution Prevention: Water Management Techniques for Pollution Prevention," Chapter 36, pp. 585-614, in *Industrial Pollution Prevention Handbook*, H. M. Freeman, editor, McGraw-Hill, New York (1995).

Peters, J., "Process Technology Winner: Water-Monsanto and Linnhoff March," *The Chemical Engineer*, No. 589, S4, May 25 (1995).

Rosain, R. M., "Reusing Water in CPI Plants," *Chem. Eng. Prog.*, 89, No. 4, 28-35, April (1993).

Rossiter, A. P. and R. Nath, "Wastewater Minimization Using Nonlinear Programming," Chapter 17, pp. 225-244, in *Waste Minimization through Process Design,* A. P. Rossiter, Editor, McGraw-Hill, New York (1995).

Rowe, D. R. and I. M. Abdel-Magid, *Handbook of Water Reclamation and Reuse,* Lewis Publishers, CRC Press, Baton Raton, FL (1995).

Shenoy, U. V., *Heat Exchanger Network Synthesis: Process Optimization by Energy and Resource Analysis*, Gulf Publishing Co., Houston, TX (1995).

Sikdar, A. K. and A. Hilaly, "Process Simulation Tools for Pollution Prevention", *Chem. Eng.*, p. 98, February (1996).

Smith, R., *Chemical Process Design*, McGraw-Hill, New York (1995a).

Smith, R., "Wastewater Minimization," in *Waste Minimization through Process Design*, A. P. Rossiter, editor, pp. 93-108, McGraw-Hill, NY (1995b).

Smith, R., E. Petela and Y. P. Wang, "Water, Water Everywhere," *The Chemical Engineer*, p. 21, May 12 (1994).

Smith, R., E. Petela and J. Howell, "Breaking a Design Philosophy," *The Chemical Engineer*, p. 21, February 22 (1996).

Soeptei, C. and F. Friedla, "Water Minimization in a Nitrocellulose Industrial Plant," *AIChE National Meeting*, Houston, TX, March (1997).

Spriggs, H. D., "An Integrated View of Industrial Water Use," *AIChE National Meeting*, Houston, TX, March (1997).

Takama, N., T. Kuriyama, K. Shiroko and T. Umeda, "Optimal Water Allocation in a Petroleum Refinery," *Comput. Chem. Eng.*, 4, 251 (1980).

Terrel, R., "Water Management in the Chemical Industry," *AIChE National Meeting*, Houston, TX, March (1997).

Tripathi, P., "Pinch Technology Reduces Wastewater", *Chem. Eng.*, 103, 87, Nov. (1996).

U. S. Environmental Protection Agency, *Manual: Guidelines for Water Reuse*, EPA/625/R-92/004, Office of Water, Washington, D.C., Sept. (1992).

Umeda, T., J. Itoh and K. Shiroko, "Heat-Exchanger System Synthesis," *Chem. Eng. Prog.*, 74, No. 7, 70 (1978).

Van Balken, H., "How to Handle Water Management in Industry," *AIChE National Meeting*, Houston, TX, March (1997).

Wang, Y. P. and R. Smith, "Wastewater Minimization," *Chem. Eng. Sci*, 49, 981 (1994a).

Wang, Y. P. and R. Smith, "Design of Distributed Effluent Treatment Systems," *Chem. Eng. Sci.*, 49, 3127 (1994b).

Wang, Y. P. and R. Smith, "Wastewater Minimization with Flowrate Constraints," *Trans. IChemE*, 73, Part A, 889 (1995).

Water Pollution Control Federation, *Water Reuse*, Manual of Practice SM-3, 2nd edition, Alexandria, VA (1989).