Part I

Overview

1

Introduction

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1.1 Chemical Process Plants

There are a wide range of chemical process industries such as agrochemicals, ceramics, cement, cosmetics, fragrances and flavors, food and drinks, glass, industrial gases, industrial/inorganic chemicals, leather, mineral processing, nuclear, oil and gas, paper and pulp, paints and pigments, petrochemicals, pharmaceuticals, polymers, rubber, soap and detergent, specialty chemicals, synthetic fibers, sugar, vegetable oils and water. Many of these involve continuous processes whereas some are batch processes. New process plants continue to be designed and built, relatively more in developing countries, to produce useful and valuable products required by the society. These are usually designed and their economic viability assessed assuming a plant life of 10 to 20 years. However, chemical plants, once built, continue to operate for very much longer than this assumed plant life.

Thus, chemical process plants in operation have been increasing steadily in the world. They were designed in the past few years or even decades, perhaps optimally for the economic, technological and societal conditions at that time. Obviously, technological knowledge has been advancing since the existing plants were designed. In addition, economic and societal conditions are dynamic and change over time for one reason or other. For example, energy prices and global warming concerns have increased substantially; new and better technologies (such as catalysts, process equipment and their internals), separation processes and intensified processes as well as simulation and optimization techniques are being continually developed and improved through research and industrial implementation.

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Hence, it is imperative to review regularly the performance of the existing plants and assess the possibilities for their improvement. This can be for one or more of the following objectives (Grossmann *et al.*, 1987; Rong *et al.*, 2000).

- To reduce energy required and/or operating cost
- To improve conversion and/or selectivity of reactions
- To increase production/throughput of the process
- To use feed of different quality and/or alternative feed
- To meet new specifications of product(s)
- To produce new products
- To enhance the control of the process
- To improve the safety, reliability and flexibility of the process
- To reduce the adverse impact of the process on the environment.

The first and relatively simple step is to optimize and set the operating conditions such as temperature, pressure and flow rate in the existing process for the chosen objective (for example, energy required and operating cost). This is often referred to as **operation optimization**, and involves analysis of the process and use of optimization techniques. In operation optimization, there is no change in process configuration or equipment. It can be performed off-line or on-line because of frequent changes in the operating environment of the process (such as product requirements and prices). On-line optimization is also known as real time optimization. Process improvement by operation optimization is limited because of constraints imposed by current process configuration, equipment and/or technology employed. It is thus necessary to consider modifications in all these for improving the current process substantially.

1.2 Process Retrofitting and Revamping

Process retrofitting and revamping refers to making suitable changes and/or additions to existing process configuration and equipment. It may involve new technology such as membrane separation or reactive distillation to supplement or replace distillation. One example of equipment and configuration changes in a process is heat exchanger network retrofitting, which involves area additions in existing exchangers and/or installation of new exchangers for increased energy recovery and re-use. Obviously, process retrofitting and revamping should maximize the use of the existing equipment in the plant as much as possible.

Analysis, simulation and optimization techniques could be used to achieve the chosen objective of process retrofitting/revamping. However, process retrofitting/revamping is more than operation optimization because the former considers changes to the process configuration and equipment in addition to operating conditions. Hence, solving a process retrofitting/revamping problem and implementing the solution found are more complex and challenging than those in the case of operation optimization.

Is there some difference between process retrofit and revamp? According to oxforddictionaries.com, revamp is to give a new and improved form, structure or appearance (to something), and retrofit is to provide (something) with a component or accessory not fitted during manufacture. Although these two meanings seem to be similar, process retrofit perhaps refers to adding new equipment to the existing process and so its scale, complexity and capital cost are relatively lower. On the other hand, process revamp involves changes in configuration and so its scale, complexity and capital cost are more. Currently, retrofit and revamp are often used synonymously in the chemical engineering literature although some practitioners use retrofit for smaller projects (that is, investment) and revamp for bigger projects.

In the technical literature, Rong *et al.* (2000) state that the main objectives of process retrofits include increasing the production capacity, efficiently processing new feedstock, utilizing new process technologies, reducing environmental impact, and reducing operating costs. According to Smith (2005), the motivation to retrofit (or revamp) an existing plant could be to increase capacity, allow for different feed or product specifications, reduce operating costs, improve safety and reduce environmental emissions. Kemp (2007), in the glossary of terms, defines retrofit or revamp as any change to an existing chemical process. On the other hand, Towler and Sinnott (2012) state that revamps fall into two categories: debottlenecking (discussed below) and retrofitting, which implies the former is not within the scope of retrofitting.

Should we distinguish retrofit/retrofitting and revamp/revamping? It is perhaps desirable for clarity and consistency. As suggested by Rao in Chapter 5, retrofitting can be used to mean adding to or replacing the whole or part of one type of equipment with a better alternative, and revamping for reorganizing the process involving several process steps (thus different equipment types). This indicates that retrofitting is smaller in scale, complexity and capital cost compared with revamping. Thus, the suggested distinction between retrofit and revamp is consistent with the use of these terms by some practitioners.

One of the purposes of process changes is to increase the plant throughput (that is, increasing production rate without any change in feed, process performance or product quality). This specific activity is referred to as ***debottlenecking***. This common term in process industries is related to a bottle's neck, which is generally narrow and limits the flow rate through it. Obviously, the neck has to be widened for increasing the flow rate. Similarly, in debottlenecking of an operating process, equipment/operation limiting the throughput is identified and then it is suitably modified for increasing the production rate. In this way, process capacity can be increased by 5 to 20%, with much smaller capital investment compared with building new facilities. This is possible because of the spare size/capacity available in many items of the existing equipment because of design margins used at the time of their design and fabrication. It is possible to increase the throughput by modifying one (type of) equipment or several types of equipment. Thus, debottlenecking can be achieved by retrofit or revamp. In other words, one objective of retrofit or revamp can be debottlenecking. Recall that retrofit and revamp can be for any of the reasons listed in the previous section. For specificity and clarity, debottlenecking (and not retrofit or revamp) should be used if the sole objective of process changes is an increase in the plant throughput. Note it is different from plant expansion, wherein there are no existing items of equipment to be considered and generally no space restrictions.

How is process retrofit/revamp different from operation optimization? Unlike the operation optimization, retrofit/revamp design will have more degrees of freedom (that is, variables related to existing equipment changes and to new equipment) and more combinations to be considered for optimization. Hence, it is much more challenging than operation optimization. However, retrofit/revamp design can improve the process significantly compared with operation optimization.

Analysis and solution of a process retrofit/revamp problem will require simulation and optimization. Hence, computational techniques for process simulation and optimization find applications in process retrofit and revamp. However, appropriate models have to be developed for process retrofit/revamp, and the resulting optimization problems have more constraints and are more challenging than are operation optimization problems.

1.3 Stages in Process Retrofitting/Revamping Projects

There are five main stages in the industrial retrofit/revamp projects. These are: (1) establishing objectives and basis for retrofit/revamp, (2) conceptual process design, (3) front-end engineering design (FEED), (4) engineering, procurement and construction (EPC), and (5) commissioning/start-up and completion. The main activities in these five stages are summarized in Table 1.1. See Chapter 2 in this book for more details on these, and Chapter 3 for safety aspects of retrofit/revamp projects.

The first stage is to establish objectives for the retrofit/revamp project, which can be one or more of the purposes listed in Section 1.1. This should be carried out comprehensively by considering plant performance and operating experience; current product demand, quality and price as well as their future projections; raw material availability, quality and price; and promising technologies and improved equipment for the process. The feasibility of achieving the set objectives for retrofit/revamp should be assessed for obtaining management approval to proceed to the next stage. Chemical engineers are the main players in the first stage, and they need to obtain required data on raw materials and product(s) from the supply and marketing departments.

In the second stage, conceptual process design is performed by chemical engineers having experience in process development and design. It can be divided into two main steps. In the first step, existing plant design and operating data are collected, a simulation model of the process is developed and validated against the design/operating data, and rating studies are performed to identify the limits of existing equipment. Thus, this step involves extensive data collection and analysis, process simulation and equipment modeling, all within the domain of chemical engineering. In the second step, several options for retrofit/revamp should be developed and assessed for their techno-economic feasibility. These options are developed by considering heat, mass and process integration (for example, heat integration by pinch analysis or optimization; see Chapter 7 in this book), as well as promising new technologies and equipment (for example, membrane separations by themselves or along with the existing distillation column; see Chapter 10 in this book), and process intensification (for example, reactive distillation) described in Chapter 5. Further, retrofit/revamp options should use existing equipment as much as possible (to reduce capital investment) and also meet space constraints in the plant. The chosen option for retrofit/revamp should be assessed for controllability and also discussed with the operators of the existing process. Most of the research on process retrofit/revamp, as well as many chapters in this book, are focused on this step of conceptual process design, and this is discussed further in the next section. The two steps in the conceptual process design require techniques and tools for process simulation, optimization and control.

Stages 3 to 5 in industrial retrofit/revamp projects are similar to those in the engineering, construction and commissioning of new plants. However, activities in these stages (outlined

Table 1.1 *Stages in retrofit/revamp projects and main activities in each of them.*

Stage	Main Activities
1. Objectives and Basis for Retrofit/Revamp	• Study product demand, quality requirements and price • Review changes in availability, quality and prices of raw materials • Review plant performance and operating experience • Study promising technologies and improved equipment for the process • Set objective(s) and basis for retrofit/revamp, and assess their feasibility
2. Conceptual Process Design	• Collect plant design and operating data • Develop and validate simulation model of the process • Perform rating studies to identify equipment limits • Develop retrofit/revamp options considering heat/process integration, promising technologies, process intensification etc. • Assess techno-economic feasibility of retrofit/revamp options to choose the best one • Evaluate controllability of the chosen option and also discuss with the operators of the existing process
3. Front-End Engineering Design (FEED)	• Prepare process flow diagrams, piping and instrumentation diagrams, equipment data/specification sheets etc. • Prepare plot, equipment and pipe layout drawings • Request quotations for equipment, construction, instrumentation, electrical work etc. • Prepare drawings of control room, shelter, plant lighting etc. • Design fire-fighting system
4. Engineering, Procurement and Construction (EPC)	• Completion of all engineering work • Procurement of all equipment • Review of constructability and related documents, and approvals • Project monitoring and construction coordination • Management of change
5. Commissioning and Completion	• As built documents review and approval • Operators training • Pre-startup safety review • Commissioning procedures and checks • Plant performance test • Documentation on project highlights, lessons learnt and retrofit/revamp opportunities in the future

in Table 1.1) should consider existing plant layout, safety, utilities and other facilities as well as the impact of the retrofit/revamp on them. The retrofit/revamp should have no or minimal impact on the existing plant operation. This means the retrofit/revamp should preferably be implemented during the routine maintenance period. In any case, the time available for construction, installation and start-up for retrofit/revamp will be limited, and so prior planning and scheduling are essential to the timely ordering and receipt of new equipment. Careful consideration should be given to available space and access for construction and installation of new equipment as well as safety of the existing plant and all personnel during the retrofit/revamp implementation. Activities in stages 3 to 5 involve engineers from many disciplines, namely, chemical, civil, electrical, environmental, instrumentation, mechanical, safety and reliability engineering. Hence, chemical engineers will have to work with engineers from other disciplines within the company and also in other companies (for example, EPC and equipment vendors).

1.4 Conceptual Process Design for Process Retrofit/Revamp Projects

As mentioned in the previous section, the conceptual process design stage of process retrofit/revamp projects is in the chemical engineering domain, and chemical engineers are responsible for this stage. Conceptual process design is also encountered in the design and development of new chemical processes and plants, referred to as grassroots or greenfield design. There is one significant difference between these two conceptual process designs. In the conceptual process design for grassroots design, a process flowsheet is developed and simulated followed by design of the individual equipment. In effect, these two major steps are carried out sequentially, which reduces complexity and computational effort. Further, there are more degrees of freedom in each of these steps.

On the other hand, conceptual process design for retrofit/revamp will have to develop a process flowsheet using (most of) the existing equipment and latest technologies. This requirement substantially increases the constraints and also potential combinations, thus making the conceptual process design of retrofit/revamp projects much more challenging. Further, the need to reuse the existing equipment in the plant in order to reduce investment makes the conceptual process design for the retrofit/revamp project plant-specific. This is because the type/size of existing equipment are unlikely to be identical in different plants.

In general, evolution and optimization are two major approaches for determining design modifications to an existing plant for achieving the retrofit/revamp objectives (Grossmann *et al.*, 1987). In the former, process engineers propose design and structural changes using targets, bounds, heuristics, insights from plant operation, knowledge on the latest technologies and experience. The proposed changes are then analyzed and evaluated through rigorous simulation. Thus, the evolution approach starts from the existing system, and the process engineer is actively engaged in developing solutions, which are likely to be more practical and acceptable to the plant personnel. It seems to be a natural approach and probably the commonly used method in the industry. However, the evolution approach involves coming up with many alternatives and their analysis. Its success depends on the experience and ingenuity of the process engineers involved.

The optimization approach requires formulation and solution of an optimization problem for determining optimal design of the process while using the existing equipment and the latest technology as much as possible. The solution involves development and evaluation of many alternatives, not by the engineer but automatically by the optimization algorithm. Although this approach is simple in principle and provides a general framework, both the formulation and solution of the optimization problem are challenging, particularly when structural changes are involved. Hence, one likes to combine the evolution and optimization approaches judiciously, for tackling conceptual process design for retrofit/revamp projects. For example, process engineer can propose a suitable process flowsheet/structure incorporating the existing equipment, which can then be simulated and optimized. Application of the evolution and optimization approaches together can be seen in Chapters 9 to 11 of this book, whereas the optimization approach alone is used and described in Chapters 7 and 12.

1.5 Research and Development in Process Retrofit/Revamp

The earliest systematic procedure for tackling retrofit/revamp problems was by Douglas and co-workers (Fisher *et al.*, 1987; Douglas, 1988). It consisted of a hierarchy of several steps: estimating bounds on the benefits from retrofitting, estimating the benefits of replacing the existing plant by the same or better process alternative, and estimating the investment and operating cost savings by making suitable changes in the process. The last step considers modifications to the main process without heat exchangers, followed by heat exchanger network design and then refining the complete process with exchangers.

In the past few decades, there have been research efforts to develop systematic methods for solving retrofit/revamp problems. For example, Uerdingen *et al.* (2003) presented an indicator-based methodology for screening the cost-saving potential of continuous processes. It consisted of decomposition analysis, retrofit solution generation and approximate economic evaluation. Jensen *et al.* (2003) extended it to include environmental and safety indicators for sustainable retrofit targets. Carvalho *et al.* (2008) developed an Excel-based software (Sustain-Pro) and added an indicator-based sensitivity analysis algorithm into the original methodology in order to accelerate the generation of retrofit solutions.

Retrofit/revamp of a particular section of processes has received significant attention. For example, many methods have been developed for heat exchanger network (HEN) retrofitting. These methods utilize pinch analysis and/or optimization techniques; see Chapter 7 in this book for more details on HEN retrofitting, and Sreepathi and Rangaiah (2014) for a review of studies on HEN retrofitting. Optimization techniques have also been applied to retrofitting batch plants; Chapter 8 in this book provides an overview of batch plant retrofitting by optimization. Although there are many studies on process retrofit/revamp techniques and applications, they are substantially fewer than those on grassroots design of chemical processes. Possible reasons for this are more complexities and challenges in tackling retrofit/revamp problems, and the possibility of applying the knowledge and expertise gained from solving grassroots design problems to retrofit/revamp problems. This can be seen from the development and application of pinch analysis and optimization techniques for HEN synthesis (that is, design) followed by their extension to HEN retrofitting.

To quantify studies on retrofit/revamp methods and applications, the Scopus database was searched for journal papers, reviews and book chapters containing retrofit, retrofitting, revamp, revamping and/or debottlenecking in the title, abstract and/or keywords. This search was carried out in three groups of journals of interest to chemical engineering. The three groups are chemical engineering main, chemical engineering-related and chemical engineering practice; and the period covered is from 1976 to 2014. The journals included in each of these groups and the total number of journal articles containing retrofit, retrofitting, revamp, revamping and/or debottlenecking in the title, abstract and/or keywords are presented in Figure 1.1.

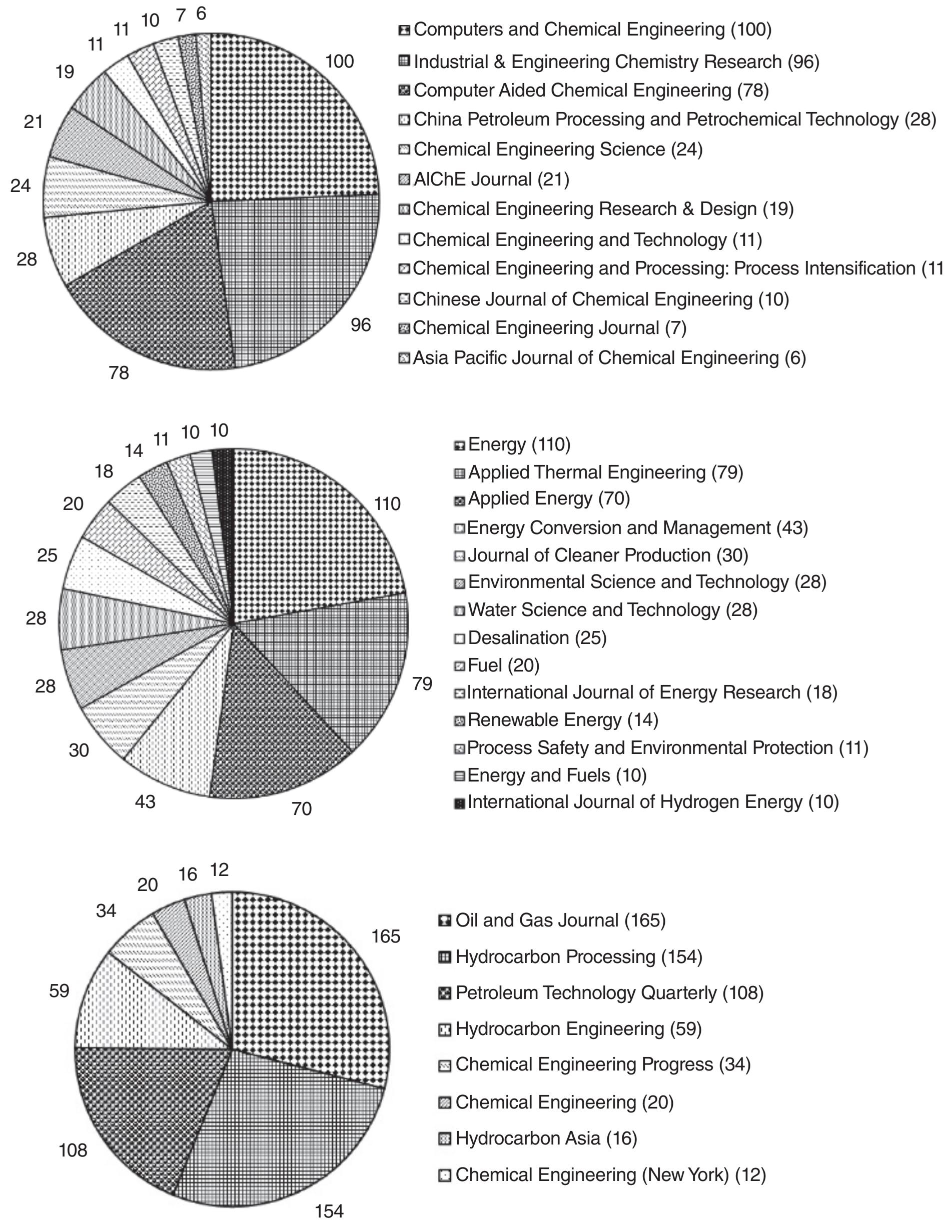

Figure 1.1 *The number of articles published from 1976 to 2014 mentioning retrofit/retrofitting, revamp/revamping and/or debottlenecking in chemical engineering main (top), -related (middle) and practice (bottom) journals.*

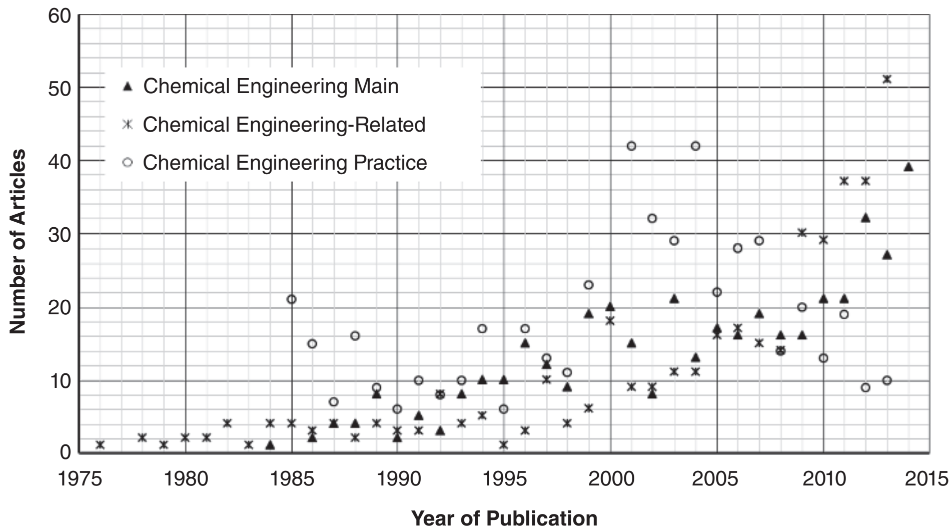

Figure 1.2 *The trend of number of articles mentioning retrofit/retrofitting, revamp/revamping and debottlenecking in the three groups of chemical engineering journals, in each year from 1976 to 2014. Note that the number of articles in chemical engineering practice in 2000 is 72, and that in chemical engineering-related in 2014 is 93; neither of these large numbers is shown in the Figure for clarity.*

The trend of the number of articles published in the three groups of journals in each year over the period covered is shown in Figure 1.2. It is clear that the number of articles related to process retrofit/revamp is increasing in chemical engineering main and -related journals. However, the number of articles mentioning process retrofit/revamp in chemical engineering practice journals went through a peak around the year 2000. Perhaps, this was due to an anticipated oil price increase after many years, and advancements in process technology, simulators and optimization software, besides optimism at the beginning of a new century.

How many of the journal articles in Figure 1.2 use retrofit/retrofitting, revamp/revamping and debottlenecking? This can be seen in Figure 1.3. Chemical engineering practitioners employ revamp more than retrofit whereas researchers mostly use retrofit. Perhaps, researchers are following the previous papers such as Grossmann *et al.* (1987), Douglas (1988) and Rong *et al.* (2000). Going by the words employed in the articles, objectives of retrofit/revamp are not just throughput increase but others listed in Section 1.1. There seems to be more articles on debottlenecking in chemical engineering main and practice journals than those in chemical engineering-related journals.

Figures 1.1 and 1.2 indicate increasing interest in process retrofit/revamp from chemical engineering researchers and substantial retrofit/revamp activity in chemical process industries. However, there seems to be only a few books and book chapters devoted to process retrofit and revamp. The book by Lieberman (2010) has many practical strategies to reuse and also improve the performance of existing equipment (such as pumps, compressors, heat exchangers, heaters and distillation columns in chemical process industries) and of several

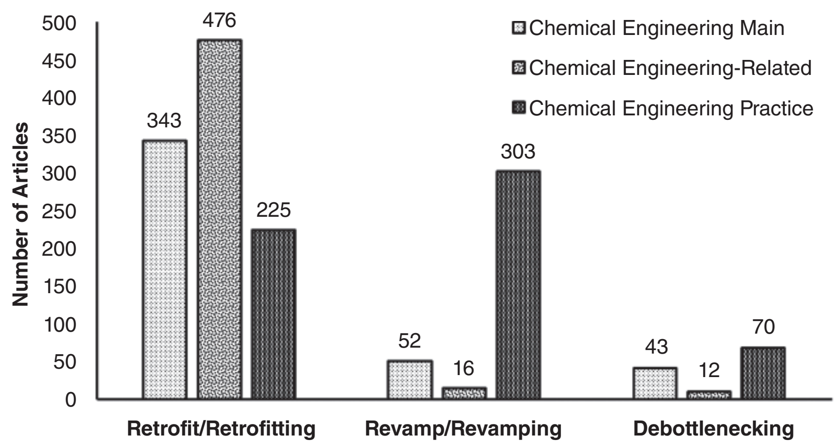

Figure 1.3 *The number of articles using retrofit/retrofitting, revamp/revamping and debottlenecking in the three groups of chemical engineering journals from 1976 to 2014.*

petroleum refining processes. It also has one chapter on summary checklist for re-using and improving common process equipment. The process design book by Douglas (1988) has one chapter on process retrofit procedure with an application to hydrodealkylation (HDA) process. The chemical engineering design book by Towler and Sinnott (2012) covers process revamps in one section of a chapter. Smith (2005) discusses retrofit of heat exchangers and their networks and distillation sequences in different sections of his book on process design and integration. Retrofit of heat exchanger networks is described in one chapter in Kemp (2007).

1.6 Scope and Organization of this Book

This book on process retrofitting and revamping is divided into three parts, each with a certain focus, for the convenience of the reader. Whereas this chapter provides an overview to process retrofitting and revamping, the next two chapters in Part I are on project engineering/management and safety aspects of process retrofitting and revamping, which are crucial for success in industrial implementation. The focus of Chapters 4 to 8 in Part II is on computational techniques for solving process retrofit/revamp problems. One of them is on process intensification technology for retrofit/revamp of chemical processes. The techniques described in Chapters 4 to 8 can be employed in a variety of process industries. Finally, Chapters 9 to 13 in Part III are on retrofit/revamp applications in chemical process industries. They describe the options considered and analysis employed for the retrofit/revamp of the process studied, which are useful for related applications.

Chapter 2 by Reddy is on project engineering and management of retrofit/revamp projects. Retrofitting and revamping projects are very common in the process industries, especially in old and aging facilities. These are increasing even in relatively new plants. However, there is very limited literature covering project engineering and management of such projects of practical importance. In Chapter 2, Reddy presents a comprehensive methodology for project engineering and management of retrofit/revamp projects, and describes important elements of retrofit/revamp project management. The significance of plant test runs, detailed pre-FEED (Front-End Engineering Design), FEED studies and project management are emphasized. Finally, retrofit/revamp options for common process equipment and systems are outlined in numerous tables, which are useful for convenient and quick reference in retrofit/revamp studies.

In **Chapter 3**, Balajee and Reddy present a comprehensive overview of all process safety aspects required for sustainable revamps. Many process safety incidents with significant impact are mainly due to unrecognized and unmitigated process safety risks. Process safety aspects are even more important for revamp projects because of complex modifications involved and/or effects of new equipment on the existing plant. Use of comprehensive process safety techniques is essential for successful implementation and operation of a revamped plant. The overview of safety aspects of revamp projects in Chapter 3 includes the application of hazard analysis methods and process hazard analysis (PHA) techniques, during Pre-FEED and FEED stages for risk assessment and risk mitigation. The importance of updating process safety information (PSI) and implementation of management of change (MOC) procedure after PHA study are emphasized. Chapter 3 is useful as a quick reference on process safety aspects for revamp projects, for both practicing engineers and students.

Part II of the book begins with **Chapter 4**, where Sharma and Rangaiah describe the modeling, simulation and optimization steps as well as software and tools for design, retrofitting and revamping of chemical processes. A general modeling procedure for process units/operations is illustrated using membrane separation for a gas mixture. This separation process is not readily available in process simulators (for example, Aspen Plus and Aspen HYSYS), and so its model is implemented in Aspen Custom Modeler (ACM) and subsequently included in process simulators. Chapter 4 discusses both deterministic and stochastic optimization techniques employed to obtain the optimal design and operating conditions of chemical processes, for single or multiple objectives. Global optimization methods have been implemented in Excel, MATLAB and C++. Therefore, interfacing a process simulator with a global optimization program is required to improve the process performance. Chapter 4 also describes interfacing of ACM, Aspen Plus and Aspen HYSYS with Excel using simple examples. Finally, the optimization of a membrane separation process for CO_2 removal from natural gas for simultaneous maximization of both methane purity and recovery, using an Excel based MOO program and Aspen Plus is presented.

In **Chapter 5**, Rao describes many opportunities of process intensification (PI) in process retrofit/revamp projects. PI, an emerging area of chemical engineering, represents a paradigm shift in process design and equipment and provides a break away from the concepts of unit operations and unit processes. It aims at orders of magnitude reduction in the sizes of equipment by enhancing the rates of transport and reaction, and in the plant footprint by combining the elementary steps such as separation and reaction. These reductions lead to inherently safer design, minimization of solvents, diluents and energy requirements. Chapter 5 also presents equipment that makes use of centrifugal fields as alternatives to distillation, absorption and extraction columns, and recently proposed modified channel geometry equipment as alternatives to stirred reactors in retrofit and revamp. Further, methods for PI like reactive and hybrid separations, heat and mass integrations (pinch technologies), conversion of processes from batch to continuous and process-specific integration are highlighted for use in the revamp. Process synthesis with PI has also been highlighted.

Dunn and Ristau, in **Chapter 6**, present graphical and mathematical design methodologies for heat and mass integration, which have been used over the past two decades to identify energy conservation and water recovery process designs in the chemical process industry. In large existing chemical plants, one is interested in the application of these design tools to identify retrofit designs where the challenge is to identify process retrofit options associated with larger systems (that is, identifying design options from the simultaneous analysis of a large number of streams). Graphical design tools allow a visualization of the design problem, not always possible when using mathematical optimization approaches. Chapter 6 focuses on two visual design strategies for solving large process integration problems. The first strategy uses visual tools for identifying heat integration designs that allow heat recovery in the industry. It uses three graphical tools, namely, temperature-interval diagram, heat pinch composite curves and the enthalpy-mapping diagram. The second strategy uses visual tools for identifying water recycle network designs that allow water use conservation and wastewater reduction in industry. This strategy uses two graphical tools: the material recycle pinch diagram and the source-sink mapping diagram. Examples of both graphical design strategies are provided.

Heat exchanger networks (HEN) retrofitting is the subject of **Chapter 7** by Sreepathi and Rangaiah. HENs are employed in process industries to decrease the external utilities required. Retrofitting existing HENs can achieve significant energy savings for a relatively small investment. Mathematical programming methods are increasingly used to solve HEN retrofitting problems. Of these, stochastic global optimization (SGO) methods such as genetic algorithm and differential evolution are gaining popularity. HEN retrofitting can be *via* modifying the HEN structure that includes adding new heat exchangers, additional area in existing exchangers, re-piping/re-sequencing existing heat exchangers and/or using heat transfer enhancements. HEN retrofitting at simple, moderate and complex levels, which are relatively easy to more difficult for implementation, and application of multi-objective optimization (MOO) are described and illustrated by applying them to retrofitting the HEN of an industrial problem having 10 hot and 5 cold streams. The objectives used are cost of retrofit and utility cost after retrofitting. MOO using the elitist non-dominated sorting genetic algorithm (NSGA-II) provides many Pareto-optimal solutions for each retrofitting level. An optimal solution can be chosen from one of these solutions based on the situation (for example, budget, manpower and time available for retrofitting).

Chapter 8 by Azzaro-Pantel deals with a number of retrofit issues dedicated to batch plants. Retrofitting is particularly important for batch processes, which have to face fluctuations in production demand, new product manufacturing and shortened time-to-market periods. Despite its significance and importance, review of the dedicated literature shows that retrofitting has received much less attention than have design problems, which can be considered as a paradoxical situation since process retrofit occurs more frequently than does process design in industrial practice. The motivation for the retrofit problem has been first provided by the industrial environment. Yet, the development of retrofit design strategies is challenging for academic research, with specific features compared with the design problem. Chapter 8 is focused on the methods and tools used to solve the batch plant retrofit problems; these methods and tools have been developed by the process systems engineering community in the last few decades. Similarities and differences with the design problem are emphasized. Conclusions and directions for future research are proposed highlighting the need for more robust retrofit strategies embedding a multi-criteria decision approach.

Part III of the book begins with **Chapter 9** by Lee *et al.* on retrofitting a side stream distillation column (SSC) for separating a ternary mixture. SSC is a common energy-intensive process and has received much scientific attention due to growing industrial demand. Recent studies and industrial applications have shown that process intensification using a dividing-wall column (DWC) can significantly reduce the energy required for the separation of mixtures by distillation. Lee *et al.* review the design and application of SSCs and DWCs in both academia and industry. A systematic procedure for the retrofit of an SSC to a DWC is presented to overcome the limited use of SSC due to the high purity requirements and low energy efficiency. Several industrial examples are presented to show the effectiveness of the procedure for retrofitting SSCs to improve the energy efficiency, thus mitigating CO_2 emissions. Various issues such as techno-economic analysis, column modification, construction and operability, are discussed briefly to provide more insight into the industrial application of DWC in the retrofit of SSCs.

Chapter 10 by Tan *et al.* is on retrofitting distillation columns for separation of olefins from paraffins in a petrochemical industry. Ethylene and propylene are the most important olefins. Owing to their similiarites in physicochemical properties with their paraffinic counterparts, their separation by cryogenic distillation requires high capital and operating costs. Hence, various alternative technologies including membrane separations have been studied by researchers. Recent studies on Carbon Molecular Sieve (CMS) membranes have shown feasibility for handling extreme operating conditions in ethylene plants. Techno-economic viability of retrofitting selected distillation columns for olefin/paraffin separation in an ethylene plant, with CMS-based membrane separation is investigated in Chapter 10. The retrofit design is optimized for two simultaneous objectives: minimize capital cost of the additional membrane unit and maximize utility cost savings of the hybrid system. Results show that the hybrid membrane-distillation system can significantly reduce the utility cost of the propylene fractionator.

In **Chapter 11**, Reddy and Rangaiah cover retrofit of vacuum systems for improving their energy efficiency. Vacuum operation is required in many process industries for a number of reasons. For this, steam jet ejectors (SJEs) are widely used due to their high reliability and medium pressure steam availability; however, they are highly inefficient. Owing to high energy prices, there is increased retrofitting of SJEs to reduce the energy cost. In Chapter 11, vacuum generation methods and options for developing energy efficient retrofit design of vacuum generation systems are analyzed. The requirements, benefits and constraints for implementation of these options are described, and a flow chart for the selection of a suitable retrofit option is presented. Practical considerations in retrofitting (for example, re-use of equipment and cooling water, plot space requirement and reliability improvement) are presented. Feasible retrofit options for both hazardous and non-hazardous applications are illustrated with one case study each. In general, numerous opportunities exist in process industries for retrofitting vacuum systems as they are widely used and need to be upgraded for revamping the process unit.

In the chemical industry, water is extensively used as a reactant, separation solvent and heating/cooling medium, and therefore the water integration is required due to both economic and environmental reasons. In **Chapter 12**, Sharma and Rangaiah present a mathematical model that can be used for grassroots and retrofit design of water networks.

Then, a large water network example in a typical petroleum refinery is analyzed for design, retrofit and revamp, using the MOO approach. Initially, MOO is employed for the design problem to explore the trade-off between fresh water consumption and total water flow rate through all regeneration units, which gives better insight and also provides many alternative optimal solutions for water network design. Two optimal water network designs are selected, and then their retrofit/revamp is studied to meet the revised environmental regulations and increased hydrocarbon load from the refinery processes. In the water network retrofit, it is assumed that there is no change in the network topology, and only capacities of the regeneration units can change. On the other hand, in the water network revamp, changes in the existing network topology along with capacities of different regeneration units are allowed. This revamp is relatively more complex and costly compared with retrofit. In this chapter, the ε-constraint method is used to obtain Pareto-optimal fronts for MOO problems.

In **Chapter 13**, Ghosh describes industrial application of debottlenecking and retrofitting of a chemical pulp refining process for paper manufacturing. The complexity of paper manufacturing depends upon the types of paper manufactured, end user applications and starting raw materials. It is a capital-intensive industry and comprises multiple process steps. Use of new technology in the form of plant and equipment to *debottleneck* many rate-determining steps and to increase throughput is often financially prohibitive. Identifying critical steps and *retrofitting* with appropriate components in such steps can be very cost-effective in the optimization of existing plants. The chemical pulp refining process is one of the most important stages for manufacturing papers and boards. In many paper mills, the installed refining system may be sub-optimal in the form of capacity, the type of refiners used, the mode of operation and the type of refiner tackles fitted. Chapter 13 presents realization of tangible benefits for two paper mills from retrofitting the refining process of paper machines. These include substantial savings in energy required for refining, increase in throughput and improvement in product quality for one mill. For the second mill, retrofitting of the existing double disc refiner by a high consistency refiner followed by a low consistency refining system enabled the mill to manufacture premium grade ‘semi-extensible’ sack kraft papers with significant improvement in the cross-directional profiles and absolute values of the critical properties of such papers.

1.7 Conclusions

Existing chemical process plants are continually increasing in number. Their performance has to be reviewed regularly, and their sustainability improved by making suitable changes in process equipment and/or structural changes. Hence, interest and activity in process retrofitting, revamping and debottlenecking are expected to grow. This book, one of the few on process retrofitting and revamping, will be useful to chemical engineering students, practitioners and researchers. Each chapter in this book can be read independently of other chapters. Hence, readers of this book can choose to read a few or all chapters, depending on their background and interest. However, they are encouraged to read the first two chapters before reading others. Many chapters in this book have exercises to solve in order to gain expertise. Most of these exercises can be given as projects in chemical engineering courses at advanced level.

This chapter introducing process retrofit/revamp and the next two chapters on project engineering and safety aspects of retrofit/revamp projects are valuable, particularly for chemical engineering students and young engineers in chemical process industries. For example, modification options for common process equipment/systems in numerous tables at the end of Chapter 2 are useful as a convenient and quick reference in retrofit/revamp studies. Computational techniques and process intensification technology for retrofit/revamp of chemical processes, described in Chapters 4 to 8, are applicable to a broad range of chemical process industries. The last five chapters (Chapters 9 to 13) describe the improvements considered and analysis employed for the retrofit/revamp of the process studied in each of them, which are useful for related applications.

The number of articles mentioning retrofit/retrofitting, revamp/revamping and debottlenecking in the chemical engineering main and -related journals, has been increasing, especially rapidly in the past five years. This is an indication of increasing research and development in process retrofit/revamp. Reviews such as Chapter 5 on process intensification technologies, Chapter 8 on batch plant retrofitting and the recent article on heat exchanger network retrofitting by Sreepathi and Rangaiah (2014) are relevant and helpful in further advancing the computational techniques and technologies for process retrofit/revamp and in increasing their applications. There will be more studies on process retrofit/revamp and successful applications in chemical process industries.

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