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Industrial Integration of Biotechnological Processes from Raw Material to Energy Integration:
Study by Modeling Approach

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14.1 Introduction: Background and Driving Forces

The design and deployment of biotechnological processes at the industrial level present many common points with the chemical engineering industry. In particular, the tools and methods used in chemical process engineering may advantageously be applied to evaluate and optimize biotechnological processes, and conversely, biotechnologies can be integrated in conventional industries to extend their range of action. In this chapter, we describe how a cross-disciplinary approach can transpose (after adaptation) relevant solutions from one sector to solve similar problems identified in another sector and improve its performance.

First, thermodynamic modeling approaches developed to increase understanding and improve the evaluation of reaction pathways is presented. A "group contribution method" that allows estimation of the Gibbs free energy of formation of (bio-)chemical products and their free energy of reaction is discussed. This approach is extended by comparing different (bio-)chemical products based on their exergy characteristics,

where exergy losses may be a helpful indication for selecting efficient products and associated processes. Disposing of a precise evaluation method for thermodynamic properties, such as reaction enthalpy or component exergy, is a first and critical step to ensure robustness and confidence in the results achieved thanks to the modeling approach.

In the second part of this chapter, the tools developed in process system engineering are applied to biological processes. These tools may be applied to study and optimize complete process flowsheets, from the upstream steps (biomass pretreatments) to the downstream ones (purification of products). For instance, the modeling approach can help to optimize upstream processing, which is increasing in importance, as biomass pretreatment steps like drying, grinding, hydrolysis, and extraction occur in practically all biomass conversion processes. In the case of microbial fuels, these steps may result in a more efficient conversion of biomass into biogas or bioethanol, for instance. Similarly, the modeling approach can be applied to the conversion and downstream processing steps. In this section, as the downstream processing of bioreactor effluents is of critical importance for the economic viability of most biotechnological processes, special attention is first paid to the description of a simple approach to optimize the selection of downstream processing steps, a methodology called "cascaded option trees." Then, a systematic approach for the optimization of the design of complete processes is described and applied to the case of biorefineries. Indeed, biorefineries are complex systems processing many different biomass feedstocks to yield a variety of different products, from fuels to heat and value-added chemicals. They are thus a perfect example to demonstrate the potential of the modeling approach for process design, integration, and optimization of complex biochemical systems.

14.2 Thermodynamic Modeling of Cell Metabolism

The use of thermodynamics provides two significant advantages that can be applied to biotechnological processes (Prausnitz, 2003). First, it has a very wide range of applications due to its universal nature based on a small number of fundamental principles. Second, it is an integrative science, and the thermodynamic properties of compounds can be largely derived from their structures thanks to molecular and statistical considerations, delivering many answers with few experimental data. These advantages are crucial in biotechnological applications due to the large variety of chemical reactions occurring at the cell level and for which the experimental collection of data is far from trivial. In order to favor the industrial integration of biotechnological processes, tools to characterize system properties, possible reactions, and their thermodynamic limitations can provide useful information.

In this section, we first present some developments applying thermodynamics to predict feasible ranges for reaction occurrence at the level of biotechnological reactors. This approach is useful, for instance, when estimating the feasibility of biodegradation pathways in order to describe an existing system, or when designing biological reactors. Then, this thermodynamic approach is extended at the process level by performing exergetic analysis of biological products. Starting from a given feedstock,

the estimation of exergy losses allows the identification of the most relevant reaction pathways for designing a new biotechnological process. These two approaches can bring significant help for the understanding and design of optimal microbial reactions and corresponding equipment.

14.2.1 Group Contribution Method

A good example of applying thermodynamic models for predicting the properties of biotechnological systems is provided by the group contribution method developed by Jankowski et al. (2008). This method allows for the determination of the standard Gibbs free energy of formation, $\Delta_f G°$, and of reaction, $\Delta_r G°$, in biotechnological processes based only on the molecular structure of the components implied in the reactions. These components are decomposed according to predefined molecular substructures to which corresponds a contribution value. Adding the contributions of all structural groups results in the total standard Gibbs free energy of formation of the molecule. The subdivision of a molecule into its structural groups must be performed with care, as the same atom could be included in several predefined groups. Thus, rules implying search priority numbers have been defined by Jankowski et al. (2008). A simple example to better understand the principle of this group contribution method consists of calculating the free energy of glucose that is used for bioethanol production. This example, shown in Table 14.1, leads to a $\Delta_f G°$ value for glucose of 218.28 kcal/mol, which is very close to the experimentally observed value of 219 kcal/mol. This method has been successfully applied for determining the $\Delta_f G°$ and $\Delta_r G°$ values for the majority of compounds and reactions described in three biochemical databases: (1) the iJR904 and iAF1260 genome-scale metabolic models of *Escherichia coli*, (2) the Kyoto Encyclopedia of Genes and Genomes, and (3) the University of Minnesota Biocatalysis and Biodegradation Database. In the last example, the standard free energy values determined by the group contribution method have been compared with experimental values for 914 compounds and 902 reactions, and the thermodynamic feasibility of 89 biodegradation pathways could be evaluated by estimating the total free energy change of each pathway (Finley et al.,

TABLE 14.1 Estimation of the Free Energy of Formation of Glucose Based on a Group Contribution Method

Identified Group	Number of Groups in the Glucose Molecule	Individual Group Contribution to $\Delta_f G°$ (kcal/mol)	Total Contribution to $\Delta_f G°$ (kcal/mol)
–OH	5	–41.5	–207.5
–O– (participating in a ring)	1	–36.6	–36.6
>CH– (participating in a ring)	5	4.84	24.2
$–CH_2–$	1	1.62	1.62
		Total	–218.28

Source: Jankowski, M. D. et al., *Biophys. J.*, 95, 1487–1499, 2008.

2009). This application proved to be a useful tool to compare competing biodegradation pathways and to identify the most thermodynamically favorable ones. As kinetic and enzymatic limitations may also play a role, this analysis is not sufficient to predict the actually occurring biodegradation pathway, but it can eliminate unfavorable candidates and provide some help in comparing the feasibility of reactions.

Finally, such thermodynamic methods can be envisaged in the case of genome-scale metabolic models (Ataman and Hatzimanikatis, 2015). It appears that a thermodynamic approach can bring significant help in the evaluation of the directionalities and of the possible flux ranges. Several examples of successful studies are mentioned by Ataman and Hatzimanikatis (2015). For instance, this approach was applied by Birkenmeier et al. (2014) to confirm glycerol-3-phosphate dehydrogenase as the enzyme controlling the glycerol anabolism in *Saccharomyces cerevisiae*. However, the development of this method is still ongoing, and many challenges remain in order to be able to identify complex bioenergetic behaviors based on thermodynamics. Such a method for estimating the Gibbs free energies of components and reactions observed in plants like maize has been used, for example, in the framework of the PlantSEED biochemistry pathways database developed by Seaver et al. (2014).

Finally, it should be mentioned that alternatives to group contribution methods have been developed for estimating thermodynamic properties in biochemical systems. Let us just mention, for instance, that Hoffmann et al. (2013) used the electrolyte perturbed-chain statistical associating fluid theory (PC-SAFT) equation of state to predict activity coefficients of methyl ferulate and the equilibrium constants of its hydrolysis reaction catalyzed by feruloyl esterase. In conclusion, it can be stated that a lot of research is still ongoing in the development of reliable models to predict thermodynamic properties in biochemical systems, leading to a better understanding and prediction of possible reaction pathways and equilibria.

14.2.2 Exergetic Evaluation of Process Alternatives

The design of new processes, including biotechnological process steps, has to include economic aspects. Unfortunately, energy prices are volatile, which directly influences operating costs and may also affect investment. These prices are strongly influenced by the political decisions of oil-producing countries, as well as political measures to ensure the long-term sustainability of the energy supply and to minimize climate change. Thus, economic evaluation of process alternatives in a way that the results remain valid in the future is difficult. Alternatively, an evaluation based on a more general measure of energy utilized may be helpful, namely, the evaluation of exergy devaluation in the sense of an exergoeconomic analysis, which is independent of energy prices (Tsatsaronis, 1996; Frenzel et al., 2013, 2014a, 2014b). Exergy is that fraction of energy which can be converted freely into any other form of energy.

The exergy of any stream in a process can be described as

$$E = E_{\text{phys}} + E_{\text{chem}} + E_{\text{mix}},$$

where the physical contribution E_{phys} results from the pressure and temperature conditions of the stream; the chemical contribution E_{chem} takes into account, for example, the free energy of formation of all components contained in the stream; and the mixing E_{mix} contribution accounts for the entropy of mixing (Frenzel et al., 2013). For a given stream, exergy is thus a state variable. For most streams in a chemical process, the chemical contribution is dominant, so that for a first evaluation, it is sufficient to regard only its change along the process. The mixing contribution is so small compared with the other contributions that it can generally be neglected. Since in biotechnological processes the conditions are typically close to ambient, which corresponds to the reference state in the definition of exergy, usually the physical contribution can be neglected as well. As a result, the exergy change associated with a biotechnological reaction directly corresponds to the free energy of the reaction at these standard conditions, as determined in Section 14.2.1. The result of such a first estimate of exergy requirement for a conversion gives the minimum energy requirement based only on the changes in chemical composition. Especially for fuel components, it is important that the energy content of the fuel is higher than the energy requirement of the process. Thus, early in process development, exergy analysis can be used to compare proposed processes against this benchmark.

Exergy as a general measure has the advantage that upon further progress in process development, all information can be used to refine the exergetic evaluation (Frenzel et al., 2014a, 2014b). This includes changes in the physical conditions, like temperature or pressure required, for which exergy losses can be estimated based on typical assumptions. For example, any heat exchanger can be evaluated assuming a typical minimum temperature difference as driving potential, and for most separation processes, reasonable assumptions lead to estimates on the exergy devaluation induced. In the next step of refinement, the exergy losses associated with individual pieces of equipment can also be accounted for, including all equipment nonidealities. Thus, exergy can be used as a general measure for energy efficiency on very different levels of detail, starting from a first rough estimate based on minimal assumptions and going to the final realization, including equipment-specific losses.

To give an impression on how exergy as a fundamental measure for process evaluation can be utilized, Figure 14.1 shows the chemical exergy of a variety of components, including fossil raw materials, biomass, intermediates, and some products of the chemical industry (Frenzel et al., 2014a, 2014b). What is striking is the fact that one of the major processes in the chemical industry, namely, the conversion of crude oil via ethylene to polyethylene, runs essentially horizontal in this diagram. It has been shown that this is a general requirement for efficient processes, because otherwise excessive energy is required to shift the exergy from a lower to a higher level (Frenzel et al., 2013). It has also been shown that this refers to the net conversion, that is, taking into account the overall exergy change of all reactants and all products. For example, if CO_2, which is shown in Figure 14.1 and has an exergetic value of essentially zero, is released during a reaction, the reactants can be converted into products of higher exergetic value without additional exergy input.

A typical example for such a process is the fermentation of sugar to ethanol, where CO_2 is released without requiring additional energy input. This process is included

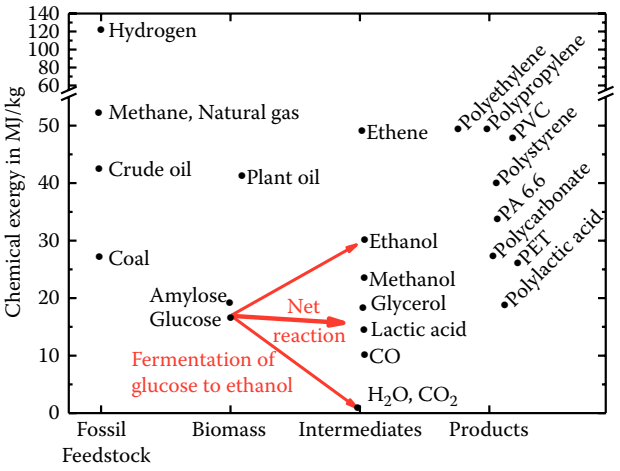

Figure 14.1 Chemical exergy of selected components from different component classes. (Reprinted with permission from Frenzel, P., and Pfennig, A., Methodik zur schnellen Bewertung von Syntheserouten auf Basis von Exergiebilanzen, presented at the ProcessNet-Jahrestagung und 32. DECHEMA-Jahrestagung der Biotechnologen, Aachen, Germany, September 12–15, 2016. http://orbi.ulg.ac.be/handle/2268/201884.)

in Figure 14.1. Of course, in this reaction one-third of the carbon originally contained in the sugar is devalued to CO_2, which corresponds roughly to the increase in exergetic value between glucose and ethanol. This example thus shows that for process evaluation, the carbon balance also has to be considered carefully, because the carbon-containing feedstock was originally produced with significant effort, which in itself can be evaluated exergetically, as well as with respect to land area used (Frenzel et al., 2014b).

For this example, the basic exergetic balances that can generally be applied for biofuels can be discussed. Pure ethanol has an exergy content of almost 30 MJ/kg. Producing the sugar as feedstock requires about 10 MJ/kg, the exergy losses of the reaction are around 3 MJ/kg as well, and the distillation requires around 4 MJ/kg, where all the values are specified with respect to the mass of the product ethanol. Without further measures, the effective exergy content of the final biofuel is thus less than half that of the ethanol, even if no further process losses are taken into account. Thus, it is apparent that the production of ethanol as biofuel can only be efficient if the energy for the process is supplied in a sustainable way, which in this example is typically realized by firing the distillation with the bagasse, which is the remainder of the original sugarcane as feedstock.

Closer inspection of Figure 14.1 also reveals that the components are essentially exergetically ordered according to their oxygen content. Components with a higher oxygen content have a lower specific exergy, which is to be expected, since the chemical exergy of a C=O bond in a molecule cannot be utilized for energy generation, since it is also contained in CO_2, which is the final product of any incineration (Frenzel et al., 2013, 2014b). Therefore, the general statements on exergy changes

during reaction can be transferred into statements on oxygen content. If the oxygen content of a component is to be decreased, this will require either significant exergy input or the elimination of a component with high oxygen content, like water or CO_2. Both eliminations lead to a loss of hydrogen or carbon in the product, which is highly undesirable.

Thus, at first sight it may appear that such an oxygen balance could replace the full exergetic evaluation. Unfortunately, oxygen balancing does not allow further refinement, for example, with respect to the evaluation of losses in process steps or equipment. As a consequence, while such carbon, hydrogen, and oxygen balances are also important for the evaluation of processes, only exergetic evaluation leads to a systematic approach that can guide process design through all design stages, from first drafts to individual equipment design.

14.3 Process System Engineering Tools for the Design of Biotechnological Processes

Once the biochemical reaction pathways have been defined, the design of the industrial process has to be considered. Besides the biochemical reactor itself, classical processes include a reactant preparation section, as well as a downstream section. In the following, we have a closer look at the selection of downstream processing steps using a cascaded option trees method. Indeed, downstream steps are often critical for the economic viability of industrial biotechnological processes. Next, we apply process system engineering tools like process design, analysis, and optimization to the case of biorefineries, as they provide an interesting example of biotechnological process integration at the industrial scale.

14.3.1 Cascaded Option Trees

One of the challenges in developing new downstream processes is the large multitude of process options that may appear feasible at the beginning of the design process. In contrast, the reaction step is often already worked out to a certain extent at this point in the design process, because engineers start to ponder over the downstream process only when the reaction toward the desired product turns out to be feasible in principle. For the reaction, on the other hand, often only minor optimizations, for example, of microbial productivity, appear to be required. At the same time, especially for bio-based processes, the properties of the media are demanding, which results as a direct consequence of the higher oxygen content of the feedstock compared with crude oil and the specifics of biotechnological processes. If, for example, high titers of the products are desired, the fermentation broth will generally have a high viscosity, and components with an increased molecular oxygen content originating from the higher oxygen content in the biomass will lead to lower vapor pressures of the target components, compared with intermediates and products of similar molar mass from fossil feedstock. Thus, distillation may no longer be the preferred option for

separation, which in turn will lead to a higher solids content, because solids have not been removed by passing through the vapor phase, and also, microbes act as solids in successive process steps. These increasingly demanding characteristics of the bio-based process streams also lead to challenges in the equipment design. Therefore, a design procedure is sought that allows systematic screening of the many process and equipment options, with the goal of finding the best option with the least design effort.

In a variety of applications, in cooperation with industry and academia, the method of cascaded option trees has been developed, which allows us to easily keep track of process options and their evaluation (Bednarz et al., 2014; the description of cascaded option trees is adopted with permission from Pfennig, 2016). The principle structure of characterizing an option in a cascaded option tree is shown in Figure 14.2. All options are listed on the regarded level of detail, and for each option, a variety of criteria can be evaluated. The evaluation can then be coded with either symbols or, for better visualization, green, yellow, and red. Application of the cascaded option trees method is shown in Figure 14.3 for an example of downstream process development, which resembles option trees developed in the mentioned cooperations. It is

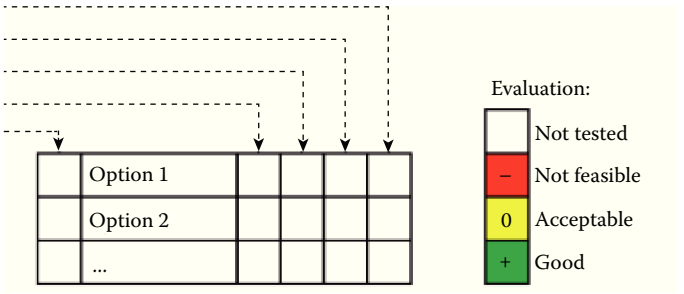

Figure 14.2 Principal representation of options in a cascaded option tree. (Reprinted with permission from Pfennig, A., Thermal unit operations, lecture manuscript. Lecture at University of Liège for Master Students in Chemical Engineering, pp. 838–848, 2016.)

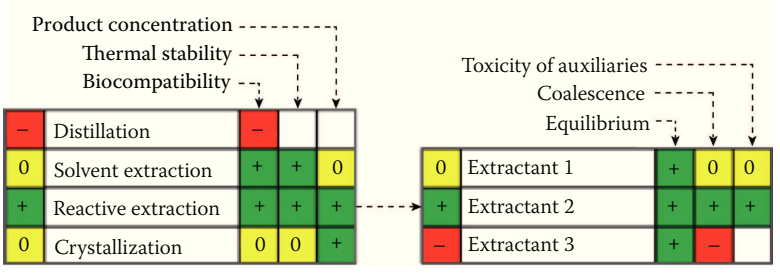

Figure 14.3 Application of cascaded option trees for an example process. (Reprinted with permission from Pfennig, A., Thermal unit operations, Lecture manuscript. Lecture at University of Liège for Master Students in Chemical Engineering, pp. 838–848, 2016.)

apparent that the method can be applied on very different cascading levels of process design, starting from overall process options and going down to specific equipment design. In the example shown, it is obvious that as soon as one of the criteria leads to the insight that an option is not feasible, this option does not need to be investigated further, so the effort for process design is minimized. The effort can be further reduced by choosing to evaluate the most critical criteria early in the evaluation process, because then the maximum number of options can be ruled out based on those criteria, avoiding effort in evaluating successive criteria.

One of the advantages of cascaded option trees is that any method can be used for the evaluation of option feasibility with respect to the design criteria. This can range from expert opinion, literature search, and simulations on different levels of detail to dedicated experiments. The source of the evaluation may be noted in the option trees as well, so that the evaluation can in principle be revised at any later time. Such flexibility also applies to the overall evaluation. Therefore, the best-suited option according to the regarded criteria is directly apparent in a well-structured way. Of course, only these optimal options will be investigated further as a first approach. However, if it then turns out in the evaluation of further criteria that these options are actually infeasible or pose significant problems, the second-best options are directly visible.

Working in project consortia, the method of cascaded option trees has also proven helpful to communicate the status of the design process, as well as the current results, in a very clearly organized way. Finally, it should be noted that upstream and reaction steps should preferably be included in the option trees from the start, since during the early stages of process development, the parameters of upstream and reaction steps, which actually may influence the downstream quite drastically, can still be adjusted relatively easily. If, for example, extractive steps are considered options in the downstream process, the nature of the fermentation medium may significantly influence coalescence behavior, which is a decisive parameter in extraction-equipment design. Thus, only if, for example, the different options for the buffer system and the fermentation medium for a biotechnological step are included while evaluating options for the downstream process, the overall optimum process can be found.

In biotechnological processes, product inhibition is frequently encountered, or the product is even toxic to the microorganisms. As a consequence, the product needs to be removed continually, ensuring a relatively low concentration in the fermenter. This can, for example, be realized by a pump-around, from which the product is removed in a separation step, preferably without the need to separate the microorganisms first. If a low product concentration in the fermenter is required, this will lead to a large flow rate of the pump-around and, correspondingly, large equipment for the separation step. Thus, while the separation may be feasible in principle, the equipment dimensions in such a case may not be. Thus, it cannot be overemphasized that in the evaluation of process options, the overall feasibility of process realization and equipment size on the desired technical scale needs to be taken into account for each option as well. Simple balances may help at this stage to gain significant insight, for example, on the flow rates required to keep product concentrations sufficiently low to avoid product inhibition at the production rate of the microorganisms.

14.3.2 Process System Engineering in Biorefineries

A biorefinery is an integrated processing facility where biomass is converted into a variety of products, ranging from value-added chemicals to fuels after many physical, chemical, and thermal conversion steps, with minimal waste and emissions. In a biorefinery, a variety of feedstocks, many products, and a large number of technologies exist. In addition, the energy needed for the conversion has to be supplied from the feedstocks or from the waste streams, so the process developers face great challenges while considering economic performance, energy requirements, and environmental impact simultaneously. A systematic approach for the design of a biorefinery integrates the use of advanced process synthesis, process analysis, and optimization methods (Antonis et al., 2012). Such comprehensive methods are crucial to developing, designing, and commercializing sustainable and cost-effective biorefineries (Yuan et al., 2013). Process synthesis methods collect the input data about different biorefinery processes and produce energetically and economically efficient biorefinery flowsheets with good operating conditions and design specifications. Process modeling and simulation are complementary approaches to analyze different designs obtained from process synthesis for the optimal configurations of biorefineries (Martín and Grossmann, 2012; Metzger et al., 2012). Over the last 45 years, researchers have studied process synthesis, and several have published extensive reviews on this subject (Hendry et al., 1973; Hlaváček, 1978; Westerberg, 1980; Nishida et al., 1981; Stephanopoulos, 1981). Recently, several researchers have been working in the field of process synthesis and the design of large-scale biorefinery systems. For example, the studies by Baliban et al. (2013) and Tay et al. (2011) addressed the determination of the single best technology for the production of single products, especially biofuels. Further, there are also some studies that take into account superstructures with multiple feedstocks, products, and conversion pathways (Santibañez-Aguilar et al., 2011; Kim et al., 2013; Murillo-Alvarado et al., 2013).

In the next sections, a brief review of advances in the area of process system engineering is provided, where available systematic techniques for process synthesis, design, integration, and optimization are introduced.

14.3.2.1 Process Flowsheeting or Synthesis

The process flowsheeting approaches are generally divided into three categories or some combination thereof: (1) methods that use heuristics, (2) methods that use thermodynamic targets and process integration, and (3) methods that use superstructures, mathematical programming, and optimization. All three approaches focus on flowsheet synthesis based on economics optimization. In the heuristic approach, one can decide whether the plant will be operated in batch or continuous, the type of reactor used, the recycle schemes for the material, the methods and sequence of separations, the energy integration applied, and so forth. In thermodynamic analysis, one has to decide the units and streams that are considered for the heat recovery, the thermodynamic targets to be used, and the level of utilities to be involved. In the optimization approach, the extent of the superstructure, the physical data included, the employed objective function, and the constraints and uncertainties to consider

are the features to be decided by engineering (Seferlis and Georgiadis, 2004). Major contributions in the first two approaches (heuristics and thermodynamic targets) are hierarchical decomposition (Douglas, 1988) and pinch analysis, which is used to identify the possible heat recovery (Linnhoff, 1993). They have been successfully applied in many industrial applications (Martín and Grossmann, 2012). A more recent trend is to combine the mathematical programming approach with algorithmic methods (or optimization techniques) that can be used effectively in process synthesis (Grossmann et al., 1999). There are three steps in the combined approach: (1) the development of a representation for alternative superstructures, (2) the formulation of a mathematical program for the selection of the configuration and operating levels from the superstructure, and (3) the solution of the optimization model (Martín and Grossmann, 2012).

14.3.2.2 Process Modeling

In the context of process synthesis, process models are necessary for simulating process flowsheets. A mathematical model is used in process simulation that represents the behavior of the process. A mathematical process model consists of a set of variables that describe important properties of the process and a set of equations that build relationships among the variables to explain the behavior of the process (e.g., heat and mass balances). For instance, the thermodynamic models mentioned in Section 14.2 are included in the process model to describe the behavior of the (bio-)chemical systems, depending on the operating conditions. Process models also include mass and energy equations describing various equipment used in the process, such as reactors or separators. For complex systems found in the chemical industry, the process models represent mostly nonlinear behaviors. With the increased interest in process synthesis, the demand for process models with increased accuracy is also growing. One important concept in process system engineering is superstructure optimization. A superstructure contains most (or all) of the system alternatives. Superstructures are defined by the process modeler, and alternative superstructures can be derived for the same process. Then, a mathematical optimization approach seeks to find the optimal configuration among the proposed alternatives (Trespalacios and Grossmann, 2014).

14.3.2.3 Process Integration

Process integration is a design approach that deals with energy efficiency, waste minimization, and the efficient use of raw materials. The process integration stage is greatly facilitated by the use of process simulations. In biorefineries, process integration plays an important role in studying strong trade-offs (Antonis et al., 2012).

14.3.2.3.1 Heat Integration. To create a heat cascade in processes, pinch analysis is a very powerful thermodynamics-based technique with a structured approach to identifying minimum energy consumption targets for heating and cooling, and the maximum internal heat recovery within a process (Linnhoff, 1993; Smith, 1995; El-Halwagi, 2008). This concept is also applicable in other areas besides heat recovery. In fact, whenever an amount (e.g., heat or mass) has a quality (e.g., temperature or concentration), the concept of composite curves can provide a view of the

problem related to the efficient recovery (or reuse) of resources. On the composite curves, the pinch point shows the location where there is an accumulated deficit of an amount above a certain quality (Gundersen, 2000). Maréchal and Kalitventzeff (1998) developed process integration techniques to study the energy supply and heat recovery in industrial processes. Duran and Grossmann (1986) proposed an algorithm for simultaneous heat integration and optimization of chemical processes. Pfeffer et al. (2007) applied process integration to a bioethanol production plant with minimization of heat demand as the optimization objective. More recently, Gassner and Maréchal (2009) developed a methodology that can be applied for the conceptual design of biofuel plants based on optimization with identification of promising flowsheets and process integration methods; they applied process synthesis on wood gasification processes.

14.3.2.3.2 Mass Integration. Mass integration is a systematic methodology for generating, separating, and allocating streams and species along the process. Mass pinch was developed by El-Halwagi and Manousiouthakis (1989, 1990), and it is applicable to industrial processes where mass exchange occurs between process streams from a number of process units, such as extractors and absorbers. They considered the transfer of a single contaminant only from a rich stream to a lean stream, where a rich stream has a higher concentration of contaminant, while a lean stream represents one with a lower concentration of the contaminant. The target in their studies was to minimize the freshwater flow rate. Mass pinch can be applied in the area of wastewater minimization where the water and wastewater are optimally used by reuse, regeneration, and recycling. Wang and Smith (1994) aimed to minimize wastewater based on maximum water reuse, and they defined the water pinch concentration and targeted the minimum freshwater consumption. Combined methods considering the heat recovery and water savings at the same time are now emerging (Ahmetovic and Grossmann, 2011).

14.3.2.4 Costing and Life Cycle Analysis

With the growing interest in sustainability, biorefineries are likely to play significant roles in enhancing energy security and mitigating climate changes. Process modeling and simulation are essential for predicting the economic, environmental, and social performance of industrial processes (Gerber et al., 2011). In the recent past, researchers have mainly focused on the development of cost-effective biorefineries that can only be achieved by optimal mass and energy integrations. In order to make the biorefinery profitable, the production of value-added products (e.g., succinic acid and dimethyl ether), the valorization of waste mass and energy streams, and cogeneration are significantly important. If a biorefinery is only producing biofuels, environmental incentives may be required. The sustainable growth of a biorefinery requires not only cost-effective products, but also energy-efficient plants. The environmental assessment of a biorefinery includes land use changes, greenhouse gas emissions, the timing of emissions, waste production, and the environmental impact of products. Some studies in literature specifically focus on the life cycle assessment of biorefineries (Ahlgren et al., 2015).

Biorefineries can use much of traditional equipment from the petrochemical industry (e.g., distillation columns, pumps, heat exchanges, and compressors), and the cost

functions for this equipment are well established (Turton et al., 2009). Conversely, some biorefinery processes are under development (e.g., gasifiers, fuel cells, and membrane separation), so their future costs are highly uncertain (Caliandro et al., 2014). Generally, the production cost goes down with an increase in plant size, and the optimal plant capacity depends on the economic value of the product. Since biomass is diluted and diversified in a vast area, a supply chain optimization and economic viability study for different sizes of biorefineries is critical for investment planning.

14.3.2.5 Process Optimization

The development of novel products from biorefineries usually focuses on the conversion of biomass, the selection of reaction pathway, and the maximum reaction yield. After that, different conversion and separation steps are included to form a biorefinery superstructure. The biorefinery superstructure can be optimized for different performance objectives, such as total cost and carbon dioxide emissions (Celebi et al., 2016). The optimization algorithm may generate different biorefinery configurations via product and technology selection, energy, and mass integration, depending on the objective of interest, raw material and utility costs, and product price. Gebreslassie et al. (2012) considered multiobjective and multiperiod optimization of biorefinery supply chains under supply and demand uncertainties. Geraili and Romagnoli (2015) used a multiobjective evolutionary algorithm to quantify the trade-offs between cost and financial risk for biorefineries. Stuart and El-Halwagi (2012) examined the integration of biorefineries into existing processes and infrastructure.

14.3.2.6 Case Study: Synthetic Natural Gas Production from Microalgae through Hydrothermal Gasification

Mian et al. (2015) have applied a systematic approach for the conceptual design of microalgae cultivation and hydrothermal gasification (Figure 14.4) by developing thermoeconomic and environmental models. Considering the energy integration principles, the multiobjective optimization (MOO) methodology has been applied to obtain a set of nondominated solutions (i.e., mathematically equally good solutions) by solving a mixed-integer nonlinear programming model. The set of nondominated solutions is referred to as a Pareto-optimal front, and each nondominated solution shows a different optimal configuration. There are three objective functions, namely, total annual cost, synthetic natural gas (SNG) production, and CO_2 emissions, in this

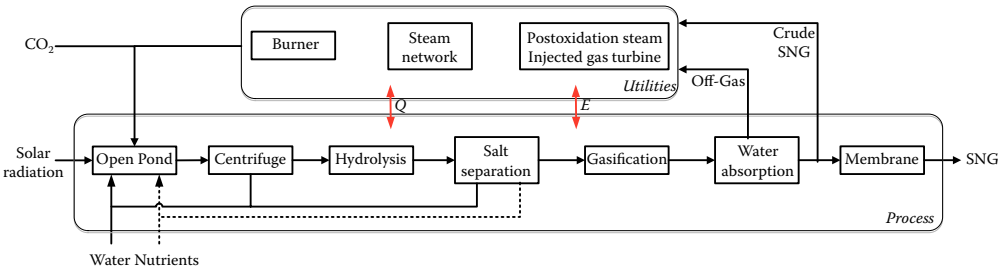

Figure 14.4 Simple flowsheet of microalgae to SNG production. (Adapted from Mian, A. et al., *Comput. Chem. Eng.*, 76, 170–171, 2015.)

optimization problem. Further, the formulated optimization problem has 11 decision variables, which are listed in Table 14.2. More details on the optimization procedure can be found in Mian et al. (2015). Figure 14.5 shows the Pareto-optimal front obtained and the selected optimal (nondominated) solutions for analyzing the effects of decision variables on the optimal designs. Table 14.2 presents the optimal values of decision variables for three selected optimal configurations. Solutions within the

TABLE 14.2 Details of Three Selected Optimal Configurations

Process Unit	Decision Variables	Selected Optimal Configurations		
		A	B	C
Salt separator	$T_{max,salts\ sep}$ [K]	744.21	787.18	851.42
	ΔT_{SSint} [K]	28.45	25.77	20.02
	$\Delta T_{SSbottom}$ [K]	20.00	29.83	30.72
	ΔT_{SStop} [K]	35.02	37.31	35.03
Hydrothermal gasification	HTG pressure	232.50	273.04	299.16
	Gasification reaction inlet temperature	623.29	623.15	623.15
Steam cycle utility	Steam pressure	66.96	61.84	60.29
	ΔT superheating	58.04	66.01	61.43
Pressure recovery expanders	Vapor high-pressure recovery	1	1	0
	Liquid high-pressure recovery	1	1	1
	Liquid low-pressure recovery	1	1	1

Source: Mian, A. et al., *Comput. Chem. Eng.*, 76, 170–183, 2015.
Note: HTG, hydrothermal gasification.

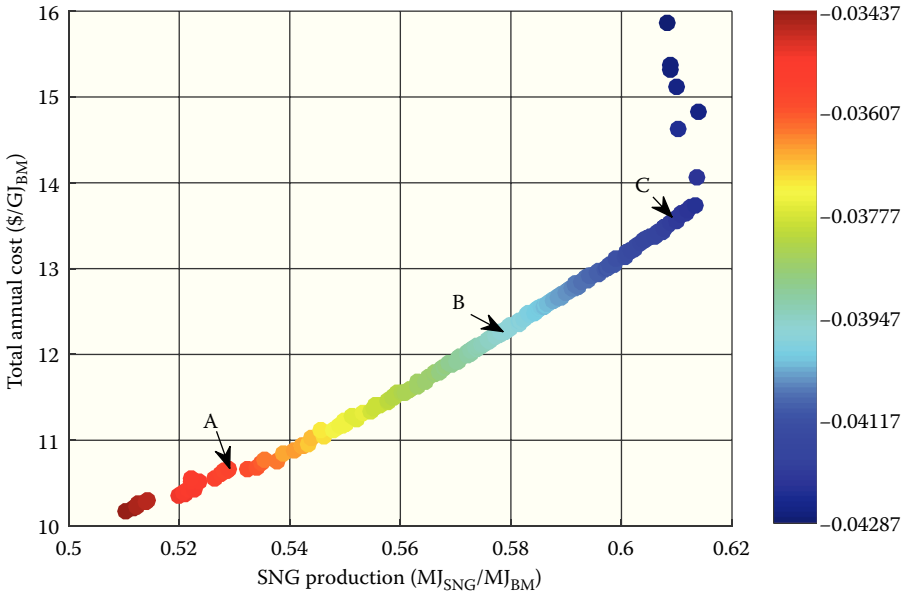

Figure 14.5 Pareto-optimal front for SNG production using microalgae; color map shows kg_{CO2}/MJ_{BM}. (Adapted from Mian, A. et al., *Comput. Chem. Eng.*, 76, 170–171, 2015.)

economic models gave a final SNG production cost of between $20 and $30/GJ SNG, which is in line with the price of fossil natural gas.

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