



PROCESS DESIGN STRATEGIES FOR BIOMASS CONVERSION SYSTEMS

DENNY K. S. NG • RAYMOND R. TAN
DOMINIC C. Y. FOO • MAHMOUD M. EL-HALWAGI



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Edited by

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AND MAHMOUD M. EL-HALWAGI

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Preface

Major environmental issues, particularly climate change, have stimulated research activities focusing on enhancing the sustainability of industrial processes. In particular, significant effort has been placed on developing viable alternatives to challenge the dominance of fossil fuels. Among the available technology options, biomass offers the possibility of a renewable supply of low-carbon feedstock for the production of clean energy, chemicals, and other products. Historically, interest in biomass as an industrial resource has peaked and waned in response to energy market trends and in fact has recently been dampened by the availability of low-cost fossil energy from nonconventional reserves; nevertheless, biomass is still widely regarded as an essential component toward the long-term development of low-carbon industries in the twenty-first century.

Research on biomass conversion is a primary requisite to the development of sustainable energy and chemical production systems. Such work is needed at different scales in order to provide the necessary scientific foundations for the improvement of existing processes, the innovation of new manufacturing routes, and the commercial deployment of new technologies. For instance, recent laboratory-scale experiments have yielded a multitude of reaction pathways for transforming a wide variety of biomass feedstocks into value-added products. The challenge of creating economically viable systems requires systematic process development approaches that lead to the synthesis and design of efficient biomass conversion facilities. Integration of the biomass conversion steps with the rest of the processing facility and utility systems offers opportunities for enhancing the efficiency and sustainability of the whole process. Furthermore, supply chain considerations should be a major component in the planning of large-scale biomass processing.

This book covers recent developments in process engineering and resource conservation for biomass conversion systems at scales ranging from the molecular level all the way to macrolevel supply chains. It provides an overview of process development in biomass conversion systems, with focus on biorefineries involving the production and coproduction of fuels, heating, cooling, and chemicals. Various techniques for enhancing the efficiency

of natural resource utilization are also covered as an essential element of developing competitive biomass-based industries. Technical, economic, environmental, and social aspects of biorefineries are discussed and integrated.

The book features 14 chapters written by leading experts from around the world and presents an integrated set of contributions that are categorized into three major sections. The first part of the book deals with *Process Design Tools for Biomass Conversion Systems* and includes five chapters. Chapters 1–3, entitled “Early-Stage Design and Analysis of Biorefinery Networks” (Peam Cheali, Alberto Quaglia, Carina L. Gargalo, Krist V. Gernaey, Gürkan Sin, and Rafiqul Gani), “Application of a Hierarchical Approach for the Synthesis of Biorefineries” (Carolina Conde-Mejía, Arturo Jiménez-Gutiérrez, and Mahmoud M. El-Halwagi), and “A Systematic Approach for Synthesis of an Integrated Palm Oil-Based Biorefinery” (Rex T. L. Ng and Denny K. S. Ng), offer systematic approaches to the conceptual design, process synthesis, and screening of alternatives in the early process development stages. Chapter 4, entitled “Design Strategies for Integration of Biorefinery Concepts at Existing Industrial Process Sites: Case Study of a Biorefinery Producing Ethylene from Lignocellulosic Feedstock as an Intermediate Platform for a Chemical Cluster” (Roman Hackl and Simon Harvey), focuses on the coupling of emerging biorefineries with existing industrial infrastructures. Chapter 5, entitled “Synthesis of Biomass-Based Tri-generation Systems with Variations in Biomass Supply and Energy Demand” (Viknesh Andiappan, Denny K. S. Ng, and Santanu Bandyopadhyay), gives a synthesis approach to the energy and mass aspects of a bioconversion system in the context of energy and mass variability in the market.

The second part of the book features three chapters on *Regional Biomass Supply Chains and Risk Management*. Chapter 6, entitled “Large-Scale Cultivation of Microalgae for Fuel” (Christina E. Canter, Luis F. Razon, and Paul Blowers), surveys recent developments in the commercial-scale production of microalgal biomass, which is considered to be one of the most promising next-generation feedstocks due to its inherently high photosynthetic efficiency. In Chapter 7, entitled “Optimal Planning Sustainable Supply Chains for the Production of Ambrox® based on *Ageratina jocotepecana* in Mexico” (Sergio I. Martínez-Guido, J. Betzabe González-Campos, Rosa E. Del Río, José M. Ponce-Ortega, Fabricio Nápoles-Rivera, and Medardo Serna-González), a process systems engineering approach to the systematic design of a large-scale biomass supply chain is described. Then, systematic risk analysis focusing on ripple effects is discussed in Chapter 8, entitled “Inoperability Input–Output Modeling Approach to Risk Analysis in Biomass Supply Chains” (Krista Danielle S. Yu, Kathleen B. Aviso, Mustafa Kamal Abdul Aziz, Noor Azian Morad, Michael Angelo B. Promentilla, Joost R. Santos, and Raymond R. Tan).

The third part of the book covers *Other Applications of Biomass Conversion Systems*. Chapter 9, entitled “Process Systems Engineering Tools for Biomass Polygeneration Systems with Carbon Capture and Reuse” (Jhuma Sadhukhan, Kok Siew Ng, and Elias Martínez-Hernandez), presents the use of techno-economic analysis and carbon dioxide (CO₂) pinch analysis techniques to develop integration configurations for CO₂ utilization and exchange in a biorefining system. Another work on cogeneration system is found in Chapter 10, entitled “Biomass-Fueled Organic Rankine Cycle-Based Cogeneration System” (Nishith B. Desai and Santanu Bandyopadhyay). Chapter 11, entitled “Novel Methodologies for Optimal Product Design from Biomass” (Lik Yin Ng, Nishanth G. Chemmangattuvalappil, and Denny K. S. Ng), discussed the use of computer-aided

molecular design technique for product design. Next, a comparative study using process integration technique between biotechnological and catalytic processes was reported in Chapter 12, entitled “The Role of Process Integration in Reviewing and Comparing Biorefinery Processing Routes: The Case of Xylitol” (*Aikaterini D. Mountraki, Konstantinos R. Koutsospyros, and Antonis C. Kokossis*). An experimental work was reported in Chapter 13, entitled “Determination of Optimum Condition for the Production of Rice Husk-Derived Bio-Oil by Slow Pyrolysis Process” (*Suzana Yusup, Chung Loong Yiin, Chiang Jinn Tan, and Bawadi Abdullah*). In the last chapter of the book, two important aspects of safety and health are reviewed in the work entitled “Overview of Safety and Health Assessment for Biofuel Production Technologies” (*Mimi H. Hassim, Weng Hui Liew, and Denny K. S. Ng*).

Together, these 14 chapters cover some of the most recent and important developments in biomass conversion systems research. We hope the book will serve as a useful guidebook for researchers and industrial practitioners working in biomass systems.

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Part 1

Process Design Tools for Biomass Conversion Systems

1

Early-Stage Design and Analysis of Biorefinery Networks

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1.1 Introduction

The limited resources of fossil fuel as well as other important driving forces (e.g., environmental, social, and sustainability concerns) are expected to shape the future development of the chemical processing industries. These challenges motivate the development of new and sustainable technologies for the production of fuel, chemicals, and materials from renewable feedstock instead of fossil fuel. An emerging technology in response to these challenges is the biorefinery concept. The biorefinery is defined as the set of processes converting a bio-based feedstock into products such as fuels, chemicals, materials, and/or heat and power.

The design of a biorefinery process is a challenging task. First, several different types of biomass feedstock and many alternative conversion technologies can be selected to match a range of products, and therefore, a large number of potential processing paths are available for biorefinery development. Furthermore, being based on a natural feedstock, the economic and environmental viability of these processes is deeply dependent on local factors such as weather conditions, availability of raw materials, national or regional subsidies and regulations, etc. Therefore, the replication of a standard process configuration is often not convenient or impossible. Designing a biorefinery, therefore, requires screening among

a set of potential configurations in order to identify the most convenient option for the given set of conditions.

Detailed evaluation of each process alternative requires a substantial amount of information such as conversions and efficiencies for the different steps involved. Moreover, considerable time and resources are needed to execute the analysis, and it is therefore not practically possible to consider more than a handful of candidate processing paths. In order to partially overcome these drawbacks, a second level of decomposition is often employed based on the so-called *development funnel* approach (see Figure 1.1). The basic idea of the development funnel approach is to progressively reduce the number of candidate alternatives by employing simplified model and shortcut evaluation methods to identify nonconvenient or nonfeasible options and eliminate those from the set of candidate configurations.

One of the challenges associated with this development funnel approach lies in the ability of performing the early-stage screening in a project phase characterized by lack of detailed data. As a consequence, it is important to simplify and manage the complexity related to the vast amount of data that needs to be processed prior to identifying the optimal biorefinery processing path with respect to economics, consumption of resources, sustainability, and environmental impact.

In order to manage the complexity and perform synthesis and design of biorefineries, several publications have focused on simplification and different aspects of the problem: the study of Voll and Marquardt (2012) explored the use of reaction flux network analysis for synthesis and design of biorefinery processing paths, Pham and El-Halwagi (2012) proposed a systematic two-stage methodology to reduce the number of processing steps, Martin and Grossmann (2012) evaluated the heat integration on a biorefinery process flowsheet producing FT-diesel, Baliban et al. (2012) studied the heat and water integration and supply chain optimization of thermochemical conversion of biomass, Zondervan et al. (2011) studied the identification of the optimal processing paths of the biochemical platform, and finally, Cheali et al. (2014) presented a generic modeling framework to manage the complexity of the multidisciplinary data needed for superstructure-based optimization of biorefinery

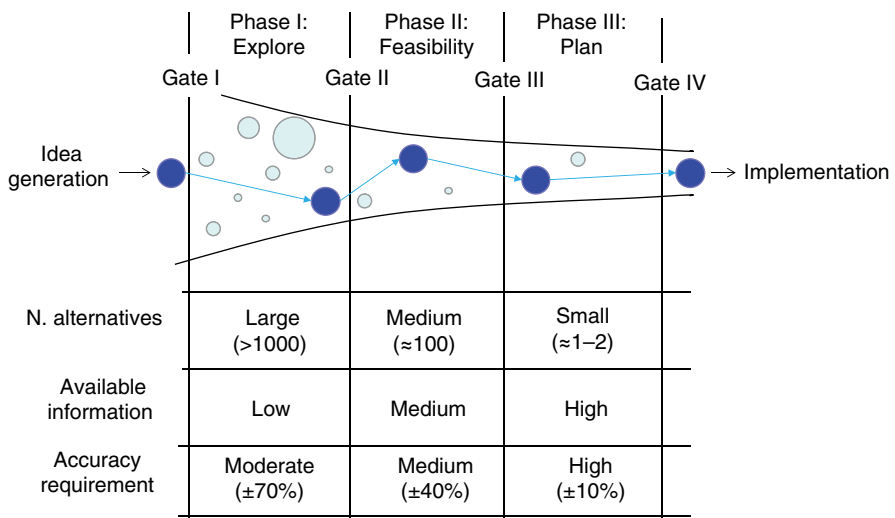


Figure 1.1 A schematic representation of the development funnel for a project in the processing industries. Reproduced from Alberto Quaglia, Ph.D. thesis, with permission

systems. A more detailed review of studies on the process synthesis of a biorefinery is given in Yuan et al. (2013).

While each of the abovementioned studies provided a valuable contribution, however, the scope of these studies was limited to one processing/conversion platform. Or, in other words, the studies focused either on biochemical, thermochemical, or biological platforms. In this contribution, as we focus on early-stage design and analysis of biorefinery systems, the scope of the biorefinery synthesis is broadened by considering a combination of thermochemical and biochemical platforms. In this way, the design space is extended significantly, meaning that more potential platforms and design alternatives can be compared resulting in a more robust and sustainable design solution. It is important to note that designing a biorefinery includes other challenges as well, such as the supply chain of the feedstock and land use, among others. These are beyond the scope of this study and will be considered in future work.

A methodology to generate and identify optimal biorefinery networks was developed earlier in our group (Zondervan et al., 2011; Quaglia et al., 2013). We present here the adaptation and extension of the methodology for the biorefinery problem. We expand the scope and the size of the biorefinery network problem by extending the database, the models, and the superstructure of the methodology with thermochemical biomass conversion routes. We then integrate the thermochemical superstructure with the superstructure of the biochemical conversion network. We then present a generic process modeling approach together with data collection and management for the multidisciplinary and multidimensional data related to different biorefinery processing steps. The optimal processing paths are then identified with respect to the given scenarios and specifications by formulating and solving an MILP/mixed-integer nonlinear programming problem (MINLP) problem using the GAMS optimization software. The resulting optimal biorefinery network is then further studied with respect to sustainability and environmental impact using two in-house software tools, SustainPro (Carvalho et al., 2013) and LCSOft (Piyarak, 2012), respectively.

1.2 Framework

This study uses the integrated business and engineering framework (Figure 1.2) which was successfully applied to synthesis and design of a wide range of different processes (Quaglia et al., 2013). The framework uses a superstructure optimization-based process synthesis combined with a generic modeling approach, thus allowing the possibility of generating a larger design space, of managing the data and model complexity, and of identifying the optimal processing path with respect to technical and economic feasibility. The framework is integrated with the analysis and evaluation of sustainability and environmental impact.

A schematic representation of the framework is reported in Figure 1.2. The description of the framework is presented step by step in this chapter:

Step 1: Problem definition

The first step includes the definition of the problem scope (i.e., design a biorefinery network, wastewater treatment plant network, a processing network for vegetable oil production), the selection of suitable objective functions (i.e., maximum profit of the biorefinery, minimum total annualized cost (TAC) of the wastewater treatment plant), and optimization scenarios with respect to either business strategy, engineering performance, sustainability, or a combination of such objectives.

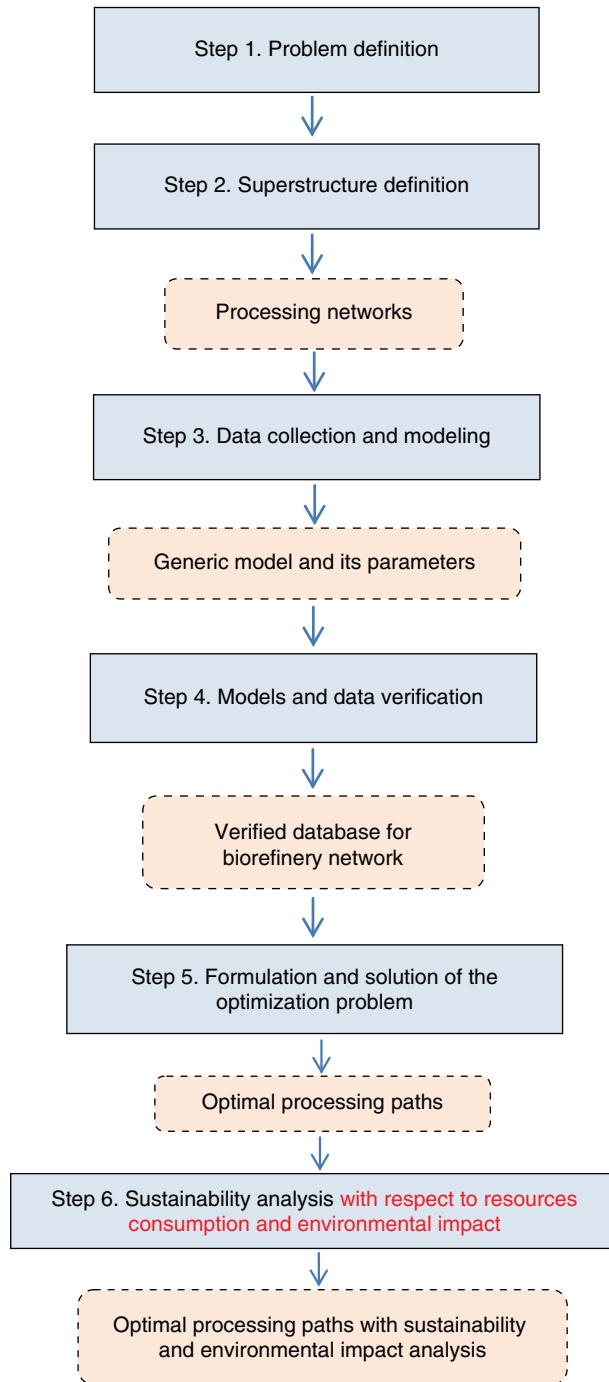


Figure 1.2 The integrated business and engineering framework adapted: the dashed boxes indicate the outcome of each step of the workflow