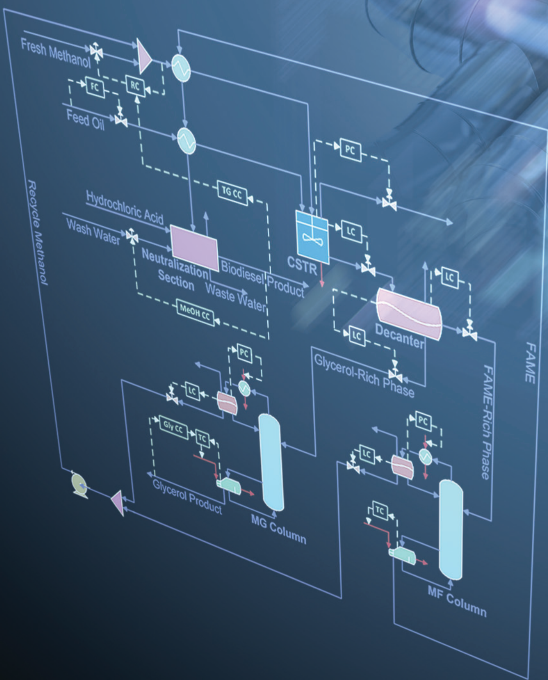
EDITORS

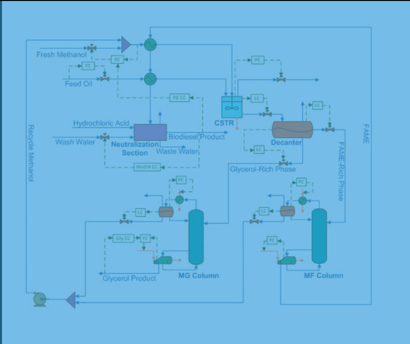
GADE PANDU RANGAIAH
VINAY KARIWALA



PLANTWIDE CONTROL

Recent Developments and Applications

WILEY



Plantwide Control

Plantwide Control

Recent Developments and Applications

Edited by

GADE PANDU RANGAIAH

Department of Chemical and Biomolecular Engineering, National University of Singapore, Singapore

VINAY KARIWALA

School of Chemical and Biomedical Engineering, Nanyang Technological University, Singapore

WILEY

A John Wiley & Sons, Ltd., Publication

This edition first published 2012

Registered office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

Library of Congress Cataloging-in-Publication Data

Rangaiah, Gade Pandu.
Plantwide control : recent developments and applications / edited by Gade Pandu Rangaiah and Vinay Kariwala.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-470-98014-9 (cloth)
1. Chemical process control. 2. Chemical plants–Management. I. Kariwala, Vinay. II. Title.
TP155.75.R356 2012
660′.2815–dc23

2011044477

A catalogue record for this book is available from the British Library.

CLOTH ISBN: 9780470980149

Set in 10/12pt Times by Aptara Inc., New Delhi, India.

Contents

Preface **xv**
List of Contributors **xvii**

Part 1 Overview and Perspectives

1 Introduction **3**
Gade Pandu Rangaiah and Vinay Kariwala

1.1 Background 3
1.2 Plantwide Control 4
1.3 Scope and Organization of the Book 6
References 9

2 Industrial Perspective on Plantwide Control **11**
James J. Downs

2.1 Introduction 11
2.2 Design Environment 12
2.3 Disturbances and Measurement System Design 14
2.4 Academic Contributions 15
2.5 Conclusions 17
References 17

Part 2 Tools and Heuristics

3 Control Degrees of Freedom Analysis for Plantwide Control of Industrial Processes **21**
N.V.S.N. Murthy Konda and Gade Pandu Rangaiah

3.1 Introduction 21
3.2 Control Degrees of Freedom (CDOF) 23
3.3 Computation Methods for Control Degrees of Freedom (CDOF): A Review 24
3.4 Computation of CDOF Using Flowsheet-Oriented Method 28
3.4.1 Computation of Restraining Number for Unit Operations 29
3.5 Application of the Flowsheet-Oriented Method to Distillation Columns and the Concept of Redundant Process Variables 35

3.6 Application of the Flowsheet-Oriented Method to Compute CDOF for Complex Integrated Processes 37
3.7 Conclusions 40
References 41

4 Selection of Controlled Variables using Self-optimizing Control Method 43
Lia Maisarah Umar, Wuhua Hu, Yi Cao and Vinay Kariwala

4.1 Introduction 43
4.2 General Principle 45
4.3 Brute-Force Optimization Approach for CV Selection 48
4.4 Local Methods 50
4.4.1 Minimum Singular Value (MSV) Rule 50
4.4.2 Exact Local Method 51
4.4.3 Optimal Measurement Combination 53
4.5 Branch and Bound Methods 56
4.6 Constraint Handling 58
4.6.1 Parametric Programming Approach 59
4.6.2 Cascade Control Approach 59
4.6.3 Explicit Constraint Handling Approach 60
4.7 Case Study: Forced Circulation Evaporator 61
4.7.1 Problem Description 61
4.7.2 DOF Analysis 62
4.7.3 Local Analysis 63
4.7.4 Selection of Measurement Subset as CVs 63
4.7.5 Selection of Measurement Combinations as CVs 64
4.7.6 Comparison using Non-linear Analysis 66
4.7.7 CV Selection with Explicit Constraint Handling 66
4.8 Conclusions 68
Acknowledgements 69
References 69

5 Input-Output Pairing Selection for Design of Decentralized Controller 73
Bijan Moaveni and Vinay Kariwala

5.1 Introduction 73
5.1.1 State of the Art 74
5.2 Relative Gain Array and Variants 75
5.2.1 Steady-state RGA 75
5.2.2 Niederlinski Index 77
5.2.3 The Dynamic RGA 78
5.2.4 The Effective RGA 79
5.2.5 The Block Relative Gain 80
5.2.6 Relative Disturbance Gain Array 81
5.3 μ-Interaction Measure 82

5.4 Pairing Analysis Based on the Controllability and Observability 83
5.4.1 The Participation Matrix 84
5.4.2 The Hankel Interaction Index Array 85
5.4.3 The Dynamic Input-Output Pairing Matrix 85
5.5 Input-Output Pairing for Uncertain Multivariable Plants 87
5.5.1 RGA in the Presence of Statistical Uncertainty 87
5.5.2 RGA in the Presence of Norm-Bounded Uncertainties 88
5.5.3 DIOPM and the Effect of Uncertainty 90
5.6 Input-Output Pairing for Non-linear Multivariable Plants 91
5.6.1 Relative Order Matrix 91
5.6.2 The Non-linear RGA 92
5.7 Conclusions 93
References 94

6 Heuristics for Plantwide Control 97
William L. Luyben

6.1 Introduction 97
6.2 Basics of Heuristic Plantwide Control 98
6.2.1 Plumbing 99
6.2.2 Recycle 99
6.2.3 Fresh Feed Introduction 102
6.2.4 Energy Management and Integration 109
6.2.5 Controller Tuning 111
6.2.6 Throughput Handle 114
6.3 Application to HDA Process 114
6.3.1 Process Description 115
6.3.2 Application of Plantwide Control Heuristics 116
6.4 Conclusions 118
References 119

7 Throughput Manipulator Selection for Economic Plantwide Control 121
Rahul Jagtap and Nitin Kaistha

7.1 Introduction 121
7.2 Throughput Manipulation, Inventory Regulation and Plantwide Variability Propagation 122
7.3 Quantitative Case Studies 125
7.3.1 Case Study I: Recycle Process 125
7.3.2 Case Study II: Recycle Process with Side Reaction 131
7.4 Discussion 142
7.5 Conclusions 144
Acknowledgements 144
Supplementary Information 144
References 144

8 Influence of Process Variability Propagation in Plantwide Control 147
James J. Downs and Michelle H. Caveness

8.1 Introduction 147
8.2 Theoretical Background 149
8.3 Local Unit Operation Control 157
8.3.1 Heat Exchanger 157
8.3.2 Extraction Process 159
8.4 Inventory Control 161
8.4.1 Pressure Control in Gas Headers 161
8.4.2 Parallel Unit Operations 164
8.4.3 Liquid Inventory Control 165
8.5 Plantwide Control Examples 169
8.5.1 Distillation Column Control 169
8.5.2 Esterification Process 171
8.6 Conclusions 175
References 176

Part 3 Methodologies

9 A Review of Plantwide Control Methodologies and Applications 181
Suraj Vasudevan and Gade Pandu Rangaiah

9.1 Introduction 181
9.2 Review and Approach-based Classification of PWC Methodologies 182
9.2.1 Heuristics-based PWC Methods 183
9.2.2 Mathematical-based PWC Methods 184
9.2.3 Optimization-based PWC Methods 185
9.2.4 Mixed PWC Methods 185
9.3 Structure-based Classification of PWC Methodologies 187
9.4 Processes Studied in PWC Applications 189
9.5 Comparative Studies on Different Methodologies 195
9.6 Concluding Remarks 196
References 197

10 Integrated Framework of Simulation and Heuristics for Plantwide Control System Design 203
Suraj Vasudevan, N.V.S.N. Murthy Konda and Gade Pandu Rangaiah

10.1 Introduction 203
10.2 HDA Process: Overview and Simulation 204
10.2.1 Process Description 204
10.2.2 Steady-state and Dynamic Simulation 206
10.3 Integrated Framework Procedure and Application to HDA Plant 206
10.3.1 Level 1.1: Define PWC Objectives 208
10.3.2 Level 1.2: Determine CDOF 209

10.3.3 Level 2.1: Identify and Analyze Plantwide Disturbances 209
10.3.4 Level 2.2: Set Performance and Tuning Criteria 209
10.3.5 Level 3.1: Production Rate Manipulator Selection 210
10.3.6 Level 3.2: Product Quality Manipulator Selection 212
10.3.7 Level 4.1: Selection of Manipulators for More Severe Controlled Variables 212
10.3.8 Level 4.2: Selection of Manipulators for Less Severe Controlled Variables 213
10.3.9 Level 5: Control of Unit Operations 214
10.3.10 Level 6: Check Component Material Balances 215
10.3.11 Level 7: Effects due to Integration 215
10.3.12 Level 8: Enhance Control System Performance (if Possible) 218
10.4 Evaluation of the Control System 218
10.5 Conclusions 223
Appendix 10A 226
References 226

11 Economic Plantwide Control 229
Sigurd Skogestad

11.1 Introduction 229
11.2 Control Layers and Timescale Separation 231
11.3 Plantwide Control Procedure 233
11.4 Degrees of Freedom for Operation 235
11.5 Steady-state DOFs 235
11.5.1 Valve Counting 236
11.5.2 Potential Steady-state DOFs 236
11.6 Skogestad's Plantwide Control Procedure: Top-down 238
11.6.1 Step S1: Define Operational Objectives (Cost J and Constraints) 238
11.6.2 Step S2: Determine the Steady-state Optimal Operation 238
11.6.3 Step S3: Select Economic (Primary) Controlled Variables, CV_1 (Decision 1) 240
11.6.4 Step S4: Select the Location of TPM (Decision 3) 244
11.7 Skogestad's Plantwide Control Procedure: Bottom-up 246
11.7.1 Step S5: Select the Structure of Regulatory (Stabilizing) Control Layer 246
11.7.2 Step 6: Select Structure of Supervisory Control Layer 248
11.7.3 Step 7: Structure of Optimization Layer (RTO) (Related to Decision 1) 248
11.8 Discussion 249
11.9 Conclusions 249
References 249

12 Performance Assessment of Plantwide Control Systems **253**
Suraj Vasudevan and Gade Pandu Rangaiah

12.1 Introduction 253
12.2 Desirable Qualities of a Good Performance Measure 254
12.3 Performance Measure Based on Steady State: Steady-state Operating Cost/Profit 255
12.4 Performance Measures Based on Dynamics 256
12.4.1 Process Settling Time Based on Overall Absolute Component Accumulation 256
12.4.2 Process Settling Time Based on Plant Production 257
12.4.3 Dynamic Disturbance Sensitivity (DDS) 257
12.4.4 Deviation from the Production Target (DPT) 257
12.4.5 Total Variation (TV) in Manipulated Variables 258
12.5 Application of the Performance Measures to the HDA Plant Control Structure 259
12.5.1 Steady-state Operating Cost 259
12.5.2 Process Settling Time Based on Overall Absolute Component Accumulation 261
12.5.3 Process Settling Time Based on Plant Production 262
12.5.4 Dynamic Disturbance Sensitivity (DDS) 263
12.5.5 Deviation from the Production Target (DPT) 265
12.5.6 Total Variation (TV) in Manipulated Variables 265
12.6 Application of the Performance Measures for Comparing PWC Systems 266
12.7 Discussion and Recommendations 268
12.7.1 Disturbances and Setpoint Changes 268
12.7.2 Performance Measures 269
12.8 Conclusions 271
References 272

Part 4 Application Studies

13 Design and Control of a Cooled Ammonia Reactor **275**
William L. Luyben

13.1 Introduction 275
13.2 Cold-shot Process 277
13.2.1 Process Flowsheet 277
13.2.2 Equipment Sizes, Capital and Energy Costs 278
13.3 Cooled-reactor Process 279
13.3.1 Process Flowsheet 279
13.3.2 Reaction Kinetics 280
13.3.3 Optimum Economic Design of the Cooled-reactor Process 282
13.3.4 Comparison of Cold-shot and Cooled-reactor Processes 286
13.4 Control 288
13.5 Conclusions 291

Acknowledgements 292
References 292

14 Design and Plantwide Control of a Biodiesel Plant **293**
Chi Zhang, Gade Pandu Rangaiah and Vinay Kariwala

14.1 Introduction 293
14.2 Steady-state Plant Design and Simulation 295
14.2.1 Process Design 295
14.2.2 Process Flowsheet and HYSYS Simulation 298
14.3 Optimization of Plant Operation 300
14.4 Application of IFSH to Biodiesel Plant 301
14.4.1 Level 1.1: Define PWC Objectives 301
14.4.2 Level 1.2: Determine CDOF 304
14.4.3 Level 2.1: Identify and Analyze Plantwide Disturbances 304
14.4.4 Level 2.2: Set Performance and Tuning Criteria 305
14.4.5 Level 3.1: Production Rate Manipulator Selection 305
14.4.6 Level 3.2: Product Quality Manipulator Selection 306
14.4.7 Level 4.1: Selection of Manipulators for More Severe Controlled Variables 306
14.4.8 Level 4.2: Selection of Manipulators for Less Severe Controlled Variables 307
14.4.9 Level 5: Control of Unit Operations 307
14.4.10 Level 6: Check Material Component Balances 307
14.4.11 Level 7: Investigate the Effects due to Integration 307
14.4.12 Level 8: Enhance Control System Performance with the Remaining CDOF 308
14.5 Validation of the Plantwide Control Structure 311
14.6 Conclusions 315
References 316

15 Plantwide Control of a Reactive Distillation Process **319**
Hsiao-Ping Huang, I-Lung Chien and Hao-Yeh Lee

15.1 Introduction 319
15.2 Design of Ethyl Acetate RD Process 321
15.2.1 Kinetic and Thermodynamic Models 321
15.2.2 The Process Flowsheet 321
15.2.3 Comparison of the Process Using either Homogeneous or Heterogeneous Catalyst 325
15.3 Control Structure Development of the Two Catalyst Systems 326
15.3.1 Inventory Control Loops 326
15.3.2 Product Quality Control Loops 328
15.3.3 Tuning of the Two Temperature Control Loops 332
15.3.4 Closed-loop Simulation Results 333
15.3.5 Summary of PWC Aspects 336

15.4 Conclusions 337
References 337

16 Control System Design of a Crystallizer Train for Para-Xylene Recovery 339
Hiroya Seki, Souichi Amano and Genichi Emoto

16.1 Introduction 339
16.2 Process Description 340
16.2.1 Para-Xylene Production Process 340
16.2.2 Para-Xylene Recovery Based on Crystallization Technology 341
16.3 Process Model 343
16.3.1 Crystallizer (Units 1–5) 343
16.3.2 Cyclone Separator (Units 9, 11) 344
16.3.3 Centrifugal Separator (Units 8, 10) 345
16.3.4 Overall Process Model 345
16.4 Control System Design 346
16.4.1 Basic Regulatory Control 346
16.4.2 Steady-state Optimal Operation Policy 347
16.4.3 Design of Optimizing Controllers 349
16.4.4 Incorporation of Steady-state Optimizer 352
16.4.5 Justification of MPC Application 357
16.5 Conclusions 357
Appendix 16A: Linear Steady-state Model and Constraints 358
References 359

17 Modeling and Control of Industrial Off-gas Systems 361
Helen Shang, John A. Scott and Antonio Carlos Brandao de Araujo

17.1 Introduction 361
17.2 Process Description 362
17.3 Off-gas System Model Development 364
17.3.1 Roaster Off-gas Train 364
17.3.2 Furnace Off-gas Train 368
17.4 Control of Smelter Off-gas Systems 370
17.4.1 Roaster Off-gas System 370
17.4.2 Furnace Off-gas System 377
17.5 Conclusions 383
References 383

Part 5 Emerging Topics

18 Plantwide Control via a Network of Autonomous Controllers 387
Jie Bao and Shichao Xu

18.1 Introduction 387
18.2 Process and Controller Networks 390

18.2.1 Representation of Process Network 390
18.2.2 Representation of Control Network 392
18.3 Plantwide Stability Analysis Based on Dissipativity 395
18.4 Controller Network Design 397
18.4.1 Transformation of the Network Topology 397
18.4.2 Plantwide Connective Stability 402
18.4.3 Performance Design 403
18.5 Case Study 405
18.5.1 Process Model 406
18.5.2 Distributed Control System Design 408
18.6 Discussion and Conclusions 409
References 413

19 Coordinated, Distributed Plantwide Control **417**
Babacar Seck and J. Fraser Forbes

19.1 Introduction 417
19.2 Coordination-based Plantwide Control 421
19.2.1 Price-driven Coordination 423
19.2.2 Augmented Price-driven Method 425
19.2.3 Resource Allocation Coordination 426
19.2.4 Prediction-driven Coordination 428
19.2.5 Economic Interpretation 429
19.3 Case Studies 430
19.3.1 A Pulp Mill Process 430
19.3.2 A Forced-circulation Evaporator System 433
19.4 The Future 437
References 439

20 Determination of Plantwide Control Loop Configuration and Eco-efficiency **441**
Tajammal Munir, Wei Yu and Brent R. Young

20.1 Introduction 441
20.2 RGA and REA 443
20.2.1 RGA 443
20.2.2 REA 444
20.3 Exergy Calculation Procedure 447
20.4 Case Studies 450
20.4.1 Case Study 1: Distillation Column 450
20.4.2 Case Study 2: Ethylene Glycol Production Plant 453
20.5 Conclusions 456
References 457

Appendix: Potential Problems with Rigorous Simulators and Possible Solutions **459**
Suraj Vasudevan, N.V.S.N. Murthy Konda and Chi Zhang

A.1 Introduction 459
A.2 Problems Encountered with Aspen HYSYS Simulation in Steady-state Mode 460
A.2.1 Steady-state Simulation for Estimating Gain Matrix (All Versions) 460
A.2.2 Transition from Steady-state to Dynamic Mode (All Versions) 461
A.3 Problems Encountered with Aspen HYSYS Simulation in Dynamic Mode 461
A.3.1 Dynamic Simulation with Recycle Closed (HYSYS v2004.2) 461
A.3.2 Dynamic Simulation in a Newer Version (HYSYS v7.1) 466
A.3.3 Dynamic Simulation in a Newer Version in the Presence of Disturbances (HYSYS v7.1) 467
A.3.4 Dynamic Simulation in a Newer Version in the Presence of Disturbances (HYSYS v7.2) 467
A.3.5 Dynamic Initialization of Vessels with Multiple Phases (HYSYS v7.1) 468
A.3.6 Numerical Errors in Dynamic Simulation (HYSYS v2004.2, v7.1 and v7.2) 469
A.3.7 Pressure-flow Solver in HYSYS Dynamic Mode (HYSYS v2004.2, v7.1 and v7.2) 469
A.3.8 Spikes in Process Variables in Dynamic Simulation (HYSYS v2004.2, v7.1 and v7.2) 469
References 471

Epilogue **473**
Index **475**

Preface

The use of control systems is necessary for safe and optimal operation of industrial processes in the presence of inevitable disturbances and uncertainties. Over the past several decades, many controller design algorithms have been proposed. A practicing engineer, however, needs to take many decisions before the controller can be designed. These decisions include choosing the variables to be controlled, the variables to be manipulated and their interconnections. The plantwide effect of these structural decisions needs to be borne in mind as the different units of a chemical plant are often highly interacting. In other words, the objective of designing a plantwide control (PWC) system is to decide: "where should the controllers be placed for safe, economic and sustainable operation of the plant?"

In the past three decades, the design of PWC systems has received significant attention from researchers working particularly in the area of chemical process control. A number of tools (e.g., for selection of variables and their pairings) have been developed. A number of competing methodologies have also emerged, which differ in terms of the tools and engineering insights (heuristics) used and the kind of model utilized. The tools and methodologies are being increasingly applied to plants that are more complex and of a larger scale. While the available tools, methodologies and application studies have been published in archived journals, they are scattered throughout the literature.

The main aim of this book is to provide a state-of-the-art compilation of established and emerging techniques for PWC design, as well as its applications, in an instructive way for the benefit of young researchers and industrial practitioners. The book is a collection of contributions from the leading researchers and industrial practitioners on PWC design. Every chapter has been reviewed by at least two experts and then thoroughly revised by the respective contributors. The review process for chapters co-authored by one of the editors has been entirely handled by the other editor. We are grateful to Dr Yi Cao for coordinating the review of one chapter co-authored by both the editors. During the review process, every attempt is made to maintain the high quality and educational value of the contributions. This has enabled us to achieve a good balance between the breadth and depth of individual topics.

To aid readability, the book has been divided into five parts. Part I (Chapters 1 and 2) provides the overview and perspectives on research and development in PWC. Several tools and heuristics for carrying out subtasks of PWC design are presented in Part II (Chapters 3–8). Part III (Chapters 9–12) deals with systematic methodologies for design and evaluation of PWC systems. Various application studies taken from chemical, petrochemical, biofuels and mineral processing industries are used to illustrate the wide applicability of these approaches in Part IV (Chapters 13–17). Some emerging topics within the scope of PWC are described in Part V (Chapters 18–20). An appendix is also included to discuss some issues that may be encountered during the use of process simulators for PWC design. The simulation files for most of the application studies described in this book are available on the accompanying website (http://booksupport.wiley.com).

This book will be useful for researchers and postgraduate students working in the area of process control. The contents of this book can be readily adopted as part of the second course on process control aimed at senior undergraduate and postgraduate students. It will also allow the industrial practitioners to adapt and apply available techniques to their plants. Furthermore, readers can choose the chapters of interest and read them independently.

We are grateful to the contributors and reviewers for their cooperation in meeting the requirements and schedule. We would like to thank our students and colleagues at the National University of Singapore and the Nanyang Technological University as well as our collaborators, who have contributed to this book in one way or another. Special thanks are due to Dr Suraj Vasudevan who assisted with the proofreading of several contributions, the handling of final submissions from contributors and the preparation of the book cover and index. Last, but not least, we would like to thank Sarah Tilley, Amie Marshall, Emma Strickland and Rebecca Stubbs of John Wiley & Sons Ltd for their editorial assistance in the production of this book.

Gade Pandu Rangaiah
Vinay Kariwala
Singapore
September 2011

List of Contributors

Souichi Amano, Mitsubishi Chemical Corporation, 3-10 Ushio-dori, Kurashiki 712-8504, Japan

Jie Bao, School of Chemical Engineering, The University of New South Wales UNSW, Sydney, NSW, Australia

Yi Cao, Department of Process and Systems Engineering, Cranfield University, Cranfield, Bedfordshire, UK

Michelle H. Caveness, Eastman Chemical Company, Kingsport, TN, USA

Antonio Carlos Brandao de Araujo, School of Engineering, Laurentian University, Sudbury, Ontario, Canada

James J. Downs, Eastman Chemical Company, Kingsport, TN, USA

Genichi Emoto, Mitsubishi Chemical Corporation, 3-10 Ushio-dori, Kurashiki 712-8504, Japan

J. Fraser Forbes, Department of Chemical and Material Engineering, University of Alberta, Edmonton, AB, Canada

Lee Hao-Yeh, Department of Chemical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan

Wuhua Hu, Department of Systems and Engineering Management, Nanyang Technological University, Singapore

Hsiao-Ping Huang, Department of Chemical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan

Chien I-Lung, Department of Chemical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan

Rahul Jagtap, Department of Chemical Engineering, Indina Institute of Technology Kanpur, Kanpur, India

Nitin Kaistha, Department of Chemical Engineering, Indina Institute of Technology Kanpur, Kanpur, India

Vinay Kariwala, School of Chemical and Biomedical Engineering, Nanyang Technological University, Singapore

N. V. S. N. Murthy Konda, Centre for Process Systems Engineering, Department of Chemical Engineering, Imperial College London, South Kensington Campus, London, SW7 2AZ, UK

William L. Lubyen, Department of Chemical Engineering, Lehigh University, Bethlehem, PA, USA

Bijan Moaveni, Department of Electrical and Electronics Engineering, K.N.Toosi University of Technology, Tehran, Iran

Tajammal Munir, Industrial Information and Control Centre, Faculty of Engineering, University of Auckland, Auckland, New Zealand

Gade Pandu Rangaiah, Department of Chemical and Biomolecular Engineering, National University of Singapore, Singapore

John A. Scott, School of Engineering, Laurentian University, Sudbury, Ontario, Canada

Babacar Seck, Department of Chemical and Material Engineering, University of Alberta, Edmonton, AB, Canada

Hiroya Seki, Chemical Resources Laboratory, Tokyo Institute of Technology, Nagatsuta, Midori-ku, Yokohama, Japan

Helen Shang, School of Engineering, Laurentian University, Sudbury, Ontario, Canada

Sigurd Skogestad, Department of Chemical Engineering, Norwegian University of Science and Technology, Trondheim, Norway

Lia Maisarah Umar, School of Chemical and Biomedical Engineering, Nanyang Technological University, Singapore

Suraj Vasudevan, Department of Chemical and Biomolecular Engineering, National University of Singapore, Singapore

Shichao Xu, School of Chemical Engineering, The University of New South Wales UNSW, Sydney, NSW 2052, Australia

Brent R. Young, Faculty of Engineering, University of Auckland, Auckland, New Zealand

Wei Yu, Faculty of Engineering, University of Auckland, Auckland, New Zealand

Chi Zhang, Department of Chemical and Biomolecular Engineering, National University of Singapore, Singapore

Part 1

Overview and Perspectives

1

Introduction

Gade Pandu Rangaiah[1] *and Vinay Kariwala*[2]
[1]*Department of Chemical and Biomolecular Engineering, National University of Singapore, Singapore*
[2]*School of Chemical and Biomedical Engineering, Nanyang Technological University, Singapore*

1.1 Background

Industrial chemical plants and processes usually involve many types of operations and numerous items of equipment operating at different temperatures and pressures. Consequently, these plants are complex and also often large in size. The safe and optimal operation of industrial chemical plants requires the maintenance of critical operating conditions such as temperature, pressure and composition at their respective optimal values as well as within safe limits. This challenging task has to be achieved in the presence of known disturbances such as throughput and product specification changes arising from variations in the market demand and requirements, as well as unknown and unmeasured disturbances in raw material composition, catalyst activity, equipment conditions and environment. Hence, a reliable and extensive monitoring and control system is essential for the safe and optimal operation of modern chemical plants.

The monitoring and control requirements from the chemical plants have led to the development of process control as an important area within the Chemical Engineering discipline. Accordingly, the majority of undergraduate programs in Chemical Engineering throughout the world have a compulsory course on process dynamics and control. Further, many of these programs include an optional course on advanced process control. Many textbooks on process dynamics and control are available, a number of them into their second or even third editions (e.g., Ogunnaike and Ray, 1994; Marlin, 2000; Bequette,

Plantwide Control: Recent Developments and Applications, First Edition. Edited by Gade Pandu Rangaiah and Vinay Kariwala.

2003; Romagnoli and Palazoglu, 2005; Riggs and Karim, 2006; Svrcek *et al*., 2006; Seborg *et al*., 2010). Advanced and specialized courses in process control such as model predictive control, digital control, robust control and nonlinear control can be found in the graduate programs in Chemical Engineering.

Numerous equipment in industrial chemical plants are inter-connected and operate together in order to achieve the desired process objective such as optimal production of a valuable product of desired quantity and quality from the raw materials. In effect, there are complex interactions between the equipment in chemical plants; these are increasing with energy and material integration and safety and optimization requirements (with consequent reduction in intermediate storage). A plantwide perspective is therefore crucial for synthesis and design of control systems for chemical plants, and this in turn has led to the development of plantwide control (PWC) as a sub-area within the broad topic of process control. This can be seen from the inclusion of one or two chapters in the more recent textbooks related to process control (e.g., Marlin, 2000; Skogestad and Postlethwaite, 2005; Svrcek *et al*., 2006; Seborg *et al*., 2010; Seider *et al*., 2010). There is also one book dedicated to plantwide control by Luyben *et al*. (1998). Another book on plantwide dynamic simulators by Luyben (2002) is also relevant and useful for PWC applications.

1.2 Plantwide Control

As an example of a typical chemical plant, consider the biodiesel production from vegetable oil by trans-esterification. The process flow diagram for this process is shown in Figure 1.1. This process has three continuous stirred tank reactors (CSTRs), two liquid-liquid phase separators, two distillation columns, a neutralization unit, a wash vessel and several heat

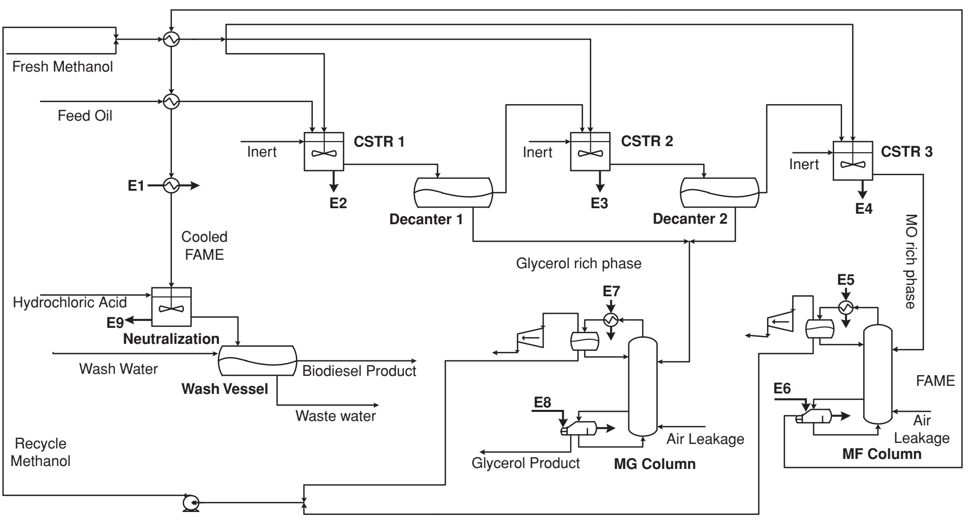


Figure 1.1 Biodiesel manufacture by transesterification of vegetable oil.

exchangers. The process features a material recycle of un-reacted methanol and an energy recycle stream for energy conservation. The liquid-liquid phase separators can have very slow dynamics due to their large inventories. A suitable thermodynamic model is necessary for predicting phase behavior in the phase separators and distillation columns. Besides the product specifications, there are upper limits on the maximum temperature (i.e., in the reboiler) of the two columns in order to avoid decomposition of biodiesel and glycerol byproduct, which also necessitate vacuum operation. A plantwide control system needs to be synthesized and designed for the complex biodiesel process for its safe and optimal operation. It should consider and maintain product purities and operating constraints as well as smoothly change the throughput in response to the variations in the feed availability and/or product demand. In fact, a control system for this plant is synthesized and tested in Chapter 14 of this book.

Accordingly, PWC refers to the synthesis and design of a control system for the complete plant considering all aspects such as throughput changes and interaction between units affecting the safe and optimal operation of the entire plant. Interaction between units has been increasing with increasing energy and mass recycling due to process optimization and with reducing inventories due to safety concerns. The main focus in PWC is on the control system synthesis considering these interactions within the plant, and not on the design of a feedback controller (although it is one part of PWC). The key questions in the control system synthesis are: which variables should be controlled, which variables should be manipulated and how should these be paired? In other words, what kind of controllers are required and where should they be placed for safe, economic and sustainable operation of the plant? In a complete plant, there are numerous choices for both controlled and manipulated variables; PWC system synthesis is therefore a large combinatorial problem. It is also a complex problem since it should consider the dynamics of all equipment in the plant.

PWC typically deals with the synthesis and development of the regulatory layer of the control system and can include supervisory layer. The former consists of ubiquitous proportional-integral-derivative (PID) controllers which directly manipulate mass and energy flow to the equipment, for example, through control valves. For complete PWC design, parameters of these feedback controllers, ratio/cascade control loops and so on also need to be specified. Complexity of PWC is also evident from the numerous PID controllers in a typical plant. On the other hand, the supervisory layer has one or more model-based/predictive controllers providing set points for some of the PID controllers in the regulatory layer.

Interest, research and development in PWC can be traced back to Buckley (1964), who developed the first procedure for PWC. Most of the developments in PWC have occurred during the last two decades. Figure 1.2 shows the number of articles published in each year during the period 1990–2010. These data were obtained by searching by topic on Web of Science for the important keywords (plantwide control, plant-wide control and reactor separator recycle control) in the subject area of Chemical Engineering. The search has found many PWC papers known to us, but it has missed some related papers (e.g., on controlled and manipulated variables selection and pairing). Note that the data shown in Figure 1.2 include conference papers. In any case, Figure 1.2 gives a good indication of the research in the area of PWC. It is clear that PWC papers have been increasing since mid-1990s, with 30–35 papers published in each of the years 2008, 2009 and 2010.

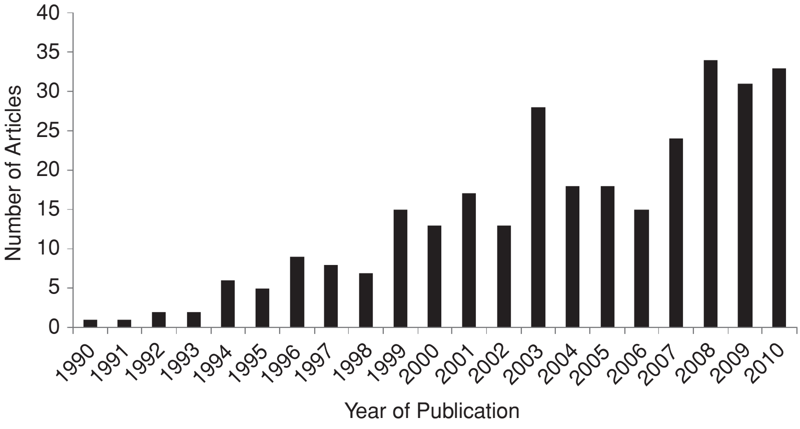


Figure 1.2 *Number of PWC articles published during the period 1990–2010.*

1.3 Scope and Organization of the Book

PWC covers selection and pairing of controlled and manipulated variables, degrees of freedom, comprehensive methodologies, realistic applications and performance assessment of control systems designed. Obviously, it requires enabling techniques and tools for these such as steady-state/dynamic simulation and controller tuning. All these are covered in this book, with emphasis on recent research and development.

This book is broadly divided into five parts. Part I (Chapters 1 and 2) provide an overview and perspectives on research and development in PWC. Several tools and heuristics for carrying out subtasks of PWC design are presented in Part II (Chapters 3–8). Part III (Chapters 9–12) deals with systematic methodologies for design and evaluation of PWC systems. Various application studies are used to illustrate the wide applicability of these approaches in Part IV (Chapters 13–17). Some emerging topics within the scope of PWC are described in Part V (Chapters 18–20). Brief overviews of these chapters are presented next.

In Chapter 2, Downs provides an industrial perspective on the past and ongoing research activities in the area of PWC. It is emphasized that industrial acceptance requires design of control strategies, which are easy to understand and can be devised in a time-efficient fashion with limited information (e.g., steady-state model). These requirements often limit the application of analytical methods based on a detailed dynamic model in process industries. Furthermore, Downs highlights the need to develop tools for the important issue of identifying the most difficult disturbances to be handled by the PWC system.

Chapters 3–5 deal with the identification and pairing of controlled and manipulated variables; these decisions are collectively known as control structure design. In Chapter 3, Konda and Rangaiah point out that the traditional method of computing control degrees of freedom (CDOF) by subtracting the number of equations from number of variables is tedious and error-prone for large-scale processes. A simple method based on the concept of restraining number for identifying CDOF is discussed in detail and illustrated using several case studies ranging from simple units to industrial processes, including a carbon capture process.

In Chapter 4, Umar, Hu, Cao and Kariwala present the self-optimizing control (SOC) based method for systematic selection of controlled variables (CVs) from available measurements. The general formulation of SOC methodology and the local methods for quick pre-screening of CV alternatives are presented. Branch and bound methods, which allow the application of local methods to large-scale systems, are discussed. The detailed case study of the forced-circulation evaporator is used to illustrate the CV selection method.

In Chapter 5, Moaveni and Kariwala provide an overview of the key methods available for selection of pairings of controlled and manipulated variables. Pairing selection methods for linear time-invariant systems are classified as relative gain array (RGA) and variants, interaction methods, and controllability- and observability-based methods. Some recent methods for pairing selection for uncertain and nonlinear processes are also discussed. Several examples are presented in tutorial fashion to aid the reader's understanding of the application of different methods.

In Chapter 6, Luyben presents some 'common-sense' heuristics which can aid the design of practical PWC systems for complex chemical processes. In particular, heuristics are presented for dealing with recycle streams and determining effective ways to feed the fresh reactant streams into the process. Some guidelines for tuning the PID controller for different loops (e.g., flow, pressure, level, temperature and composition) with a plantwide perspective are also provided. The toluene hydrodealkylation (HDA) process is used to illustrate the application of these heuristics.

In Chapter 7, Jagtap and Kaistha discuss the choice of the throughput manipulator (TPM). A heuristic for selecting the TPM for tight bottleneck/economically dominant constraint control and designing the PWC system around the selected TPM is suggested. The effect of the TPM choice on the economic performance of two realistic chemical processes is evaluated. It is shown that the suggested heuristic provides better economic performance than the conventional practice of using the fresh process feed as the TPM.

In Chapter 8, Downs and Caveness highlight that the PWC system is a mechanism to shift process disturbances and process variability from harmful locations to other locations that have less risk, harm or cost to the overall plant. Thus, viewing the process control system as a variability change agent can provide insights into PWC system development and analysis. Theoretical analysis and realistic examples are presented to signify the effect of choosing inventory location and size, TPM and strategies for managing recycle streams or the management of process variability.

In Chapter 9, Vasudevan and Rangaiah present a review of PWC design methodologies and applications. The available PWC methodologies are classified based on their approach and their brief overview is provided. The structure-based classification of PWC methodologies is also presented. The industrial processes considered in the reported PWC studies are listed together with their main features. Finally, PWC comparative studies performed to date are reviewed.

In Chapter 10, Vasudevan, Konda and Rangaiah present the integrated framework of simulation and heuristics (IFSH) as an effective and practical PWC system design method. The main emphasis of this methodology is the use of steady-state and dynamic simulations of the plant throughout the procedure to make the right decision from those suggested by heuristics. The IFSH procedure is illustrated on the modified HDA process featuring a membrane separator in the gas recycle loop. Analysis of the results indicates that the integrated framework builds synergies between the powers of both simulation and heuristics, to yield a stable and robust PWC structure.

Chapter 11 is on the PWC procedure of Skogestad. An important feature of this procedure is to start with the optimal *economic* operation of the plant and then attempt to design a control structure that implements optimal operation, while also considering the more basic requirements of robustness and stability. The procedure is split into a top-down part, based on plant economics, and a bottom-up part. The bottom-up parts aims to find a simple and robust 'stabilizing' or 'regulatory' control structure, which can be used under most economic conditions.

In Chapter 12, Vasudevan and Rangaiah present reliable quantitative criteria for comprehensively analyzing and comparing the performance of different PWC structures. These criteria include dynamic disturbance sensitivity, deviation from the production target, total variation in manipulated variables, process settling time and steady-state economic measure. These measures are applied to the PWC system developed for the modified HDA process in Chapter 10. The authors also provide some recommendations for comprehensive performance assessment of PWC systems.

In Chapter 13, Luyben considers control of an ammonia process containing multiple adiabatic reactors with 'cold-shot' cooling. It is demonstrated that a cooled ammonia reactor is much more economical because of lower-pressure operation (less feed compressor work), smaller recycle gas flow rates (less recycle compressor work) and recovery of the exothermic heat of reaction by generating steam. A PWC system is developed and shown to provide effective regulatory control for large disturbances.

In Chapter 14, Zhang, Rangaiah and Kariwala consider a biodiesel production plant. Different alternative designs for the production of biodiesel through alkali-catalyzed transesterification of vegetable oil are considered and a suitable design is selected. A complete PWC structure is then designed using the IFSH procedure and is shown to give stable and satisfactory performance in the presence of expected plantwide disturbances.

In Chapter 15, Huang, Chien and Lee discuss the design and control of reactive distillation processes. Two important operations (reaction and separation) are carried out in a single vessel in reactive distillation, which makes the control of this process difficult. For reactive distillation of ethyl acetate with homogeneous and heterogeneous catalysts, optimal designs are developed and PWC systems are designed systematically. The performance of the homogeneous catalyst process is considerably inferior as compared to that of the heterogeneous catalyst process due to slow reaction rate, which highlights the effect of process chemistry on the control performance.

In Chapter 16, Seki, Amano and Emoto design a control system for a multistage crystallization process that is part of the product recovery section of an industrial para-xylene production plant. Multiloop PID and model predictive controllers (MPCs) are designed for this process. Closed-loop simulations show the superior performance of MPC. The possibility of constraint switching using a steady-state optimizer to enlarge the feasible operation region is evaluated.

The economic PWC procedure discussed in Chapter 11 is applied to an off-gas system by Shang, Scott and de Araujo in Chapter 17. Dynamic models for the off-gas systems of a smelter's roasters and furnaces are developed using fundamental principles. It is shown that the PWC system allows near-optimal economic operation of this process, while complying with environmental regulations by avoiding emission of hazardous off-gases to the atmosphere.

In Chapter 18, Bao and Xu study PWC from a network perspective. The process is modeled as a network of process units interconnected via mass and energy flow, and a network of distributed controllers is employed to control the process network. Modeling of the process and controller networks is discussed. The effects of the interactions between process units on plantwide stability are analyzed. Lastly, an approach is presented for control network design to achieve plantwide performance and stability, even when the communication system breaks down.

In Chapter 19, Seck and Forbes discuss approaches for distributed PWC. It is highlighted that co-ordinated distributed schemes provide a good trade-off between the advantages of the centralized and decentralized approaches. For co-ordinated PWC, overviews of price-driven resource allocation and prediction-driven schemes are provided. Two case studies, namely, a pulp mill process and a forced circulation evaporator, are used to illustrate the advantages and disadvantages of the different approaches.

In Chapter 20, Munir, Yu and Young propose eco-efficiency as a way to integrate process design and control. The thermodynamic concept of exergy is used to analyze the process in terms of its efficiency. The focus of this chapter is on input-output pairing selection using relative exergy array (REA), which measures both the relative exergetic efficiency and controllability of a process. Case studies involving distillation columns are used to show that the combination of RGA and REA can guide the process designer to reach the optimal control design with low cost.

Rigorous process simulators are being increasingly used in PWC studies. In the Appendix of this book, Vasudevan, Konda and Zhang share their experience on the use of Aspen HYSYS as part of their extensive PWC studies. Selected problems faced by them and the different solutions that they tried and employed to overcome the problems are presented. In addition, some general problems together with possible solutions are also discussed.

In summary, this book provides researchers and postgraduate students with an overview of the recent developments and applications in the area of PWC. It will also allow industrial practitioners to adapt and apply the available techniques to their plants. Contents of this book can be readily adopted as part of the second course on process control aimed at senior undergraduate and postgraduate students. The reader can also study chapters of interest, independent of the rest of the book.

References

Bequette, B.W. (2003) *Process Control: Modeling, Design and Simulation*, Prentice Hall, Upper Saddle River.

Buckley, P.S. (1964) *Techniques of Process Control*, John Wiley & Sons, New York.

Luyben, W.L. (2002) *Plantwide Dynamic Simulators in Chemical Processing and Control*, CRC Press, New York.

Luyben, W.L., Tyreus, B.D. and Luyben, M.L. (1998) *Plantwide Process Control*, McGraw-Hill, New York.

Marlin T.E. (2000) *Process Control: Designing Processes and Control Systems for Dynamic Performance*, 2nd edn, McGraw Hill, New York.

Ogunnaike, B.A. and Ray, W.H. (1994) *Process Dynamics, Modeling and Control*, Oxford University Press, New York.
Riggs, J.B. and Karim, M.N. (2006) *Chemical and Bio-Process Control*, Prentice Hall, Boston.
Romagnoli, J. and Palazoglu, A. (2005) *Introduction to Process Control*, CRC Taylor & Francis, Boca Raton.
Seborg, D.E., Edgar, T.F., Mellichamp, D.A. and Doyle, F.J. III (2010) *Process Dynamics and Control*, 3rd edn, John Wiley & Sons, Hoboken.
Seider, W.D., Seader, J.D., Lewin, D.R. and Widagdo, S. (2010) *Product and Process Design Principles: Synthesis, Analysis and Evaluation*, 3rd edn, John Wiley & Sons, New York.
Skogestad, S. and Postlethwaite, I. (2005) *Multivariable Feedback Control: Analysis and Design*, 2nd edn, John Wiley & Sons, Chichester.
Svrcek, W.Y., Mahoney, D.P. and Young, B.R. (2006) *A Real-Time Approach to Process Control*, 2nd edn, John Wiley & Sons, Chichester.