# 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

COPYRIGHTED MATERIAL

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**