SUSTAINABLE PROCESS ENGINEERING
CONCEPTS, STRATEGIES, EVALUATION, AND IMPLEMENTATION
# Contents

**Acknowledgements**  
**Preface**

**PART A: CONCEPTS**

**Introduction to Part A**  

1. **Sustainability Concepts**  
   1.1 The Concept of Sustainable Development  
   1.2 Sustainability in the Context of the Process Industries  
   1.3 Some Temporal Characteristics of Sustainability  
      1.3.1 Time Horizons in Project Evaluation  
      1.3.2 Time Horizons for Technology Development  
      1.3.3 Time Dependence of Technology Improvement  
      1.3.4 Robustness to Technological, Economic, and Regulatory Change  
      1.3.5 Appraisal of Uncertainties (Technical, Business, and Environmental)  
   1.4 The Sustainable Project or Industry  
   1.5 Conflicts in Achieving Sustainability Objectives

2. **Cleaner Production**  
   2.1 Introduction  
   2.2 The Concept of 'Cleaner Production'  
   2.3 The Product Life Cycle  
   2.4 Hierarchy of Waste Management  
   2.5 Concepts and Sources of Waste  
      2.5.1 Concepts of Waste  
      2.5.2 Process and Utility Waste  
      2.5.3 Utility Waste and System Boundary Definition  
      2.5.4 Packaging
2.6 Impacts of Waste 27
2.7 Classification of Waste 27
2.8 Driving Forces for Cleaner Production 28
2.9 Resistance to Introducing Cleaner Production 28
2.10 Concluding Remarks 29

3 Industrial Ecology 31
3.1 The Basic Concept of Industrial Ecology 31
3.2 Energy and Materials Recovery from Waste Streams 34
3.3 Resource Flow through the Economy 34
  3.3.1 Sulphur Flow in Australia 34
3.4 Transport and Storage of Raw Materials and Products 35
  3.4.1 Marine Transport 36
  3.4.2 Road and Rail Transport 36
3.5 Integrated Site Manufacture 36
3.6 Some Examples of Industrial Ecology Initiatives 38
  3.6.1 Case 1: Hydrogen Utilisation from Refineries 38
  3.6.2 Case 2: Fertiliser Complex, Queensland, Australia 39
  3.6.3 Case 3: Industrial Integration at Kalundborg, Denmark 40
  3.6.4 Case 4: Industrial Symbiosis at Kwinana, Western Australia 41
3.7 Concluding Remarks 42

Problems: Part A 45

PART B: Strategies 53

Introduction to Part B 53

4 Waste Minimisation in Reactors 55
4.1 Introduction 55
4.2 A Checklist for Reaction Systems and Reactors 56
4.3 Chemistry of Process Route 57
  4.3.1 Conversion, Selectivity, and Yield 59
  4.3.2 Co-Product and By-Product Utilisation 60
4.4 Impurities in Reactor Feedstocks 60
4.5 Mixing of Reactants 62
  4.5.1 Mixing of Gaseous Reactants 62
  4.5.2 Mixing of Liquids 62
  4.5.3 Fluid Distribution in Packed Bed Reactors 62
4.6 Minimising Secondary Reactions 63
4.7 Recycle of Unreacted Feed from Reactor Outlet 64
4.8 Reversible Reactions 64
4.9 Catalysis 65
  4.9.1 Example of the Effect of Catalyst Activity on Performance 66
4.10 Agent Materials 67
4.11 Case Examples 67
4.12 Chlor-Alkali Production in Mercury Cell 68
  4.12.1 Transport Paths 69
  4.12.2 Other Aspects of the Mercury Cell Chlorine Process 71
4.13 Ethylene Manufacture from Hydrocarbons 71
4.14 Hydrogen Cyanide Manufacture from Ammonia, Methane, and Air 73
4.15 Sulphuric Acid Manufacture 75
4.16 PVC Production by Suspension Polymerisation of Vinyl Chloride Monomer 78
4.17 Concluding Remarks 80

5 Waste Minimisation in Separation Processes 83
5.1 Classification of Separation Processes 83
5.2 Sources of Waste in Separation Processes 84
5.3 Distillation 85
5.4 Gas Absorption 87
5.5 Adsorption 90
5.6 Filtration 91
  5.6.1 Centrifugal Separation 92
  5.6.2 Filtration of Solids from Gas Streams 92
  5.6.3 Separation of Liquid Particulates from Gas Streams 92
5.7 Drying 93
5.8 Evaporation and Condensation 93
5.9 Solid–Liquid Extraction 94
5.10 Liquid–Liquid Extraction 95
5.11 Use of Extraneous Materials 95
  5.11.1 Example of Extraneous Material Use — Sulphuric Acid in Chlorine Drying 96
5.12 Case Examples 97
  5.12.1 Case Example — Solid Sodium Cyanide Plant 98
5.12.2 Other Case Examples of Gas Absorption in Chemical Processes
5.12.3 Case Examples in Distillation
5.13 Concluding Remarks

6 Identification of Waste in Utility Systems
6.1 Introduction
6.2 Fuels
6.3 Fuel Combustion
   6.3.1 Heat of Combustion
   6.3.2 Excess Air
6.4 Common Fuels
6.5 Environmental Impacts of Flue Gases
   6.5.1 NO* Formation in Fuel Combustion
6.6 Theoretical Flame Temperatures
6.7 Furnaces
6.8 Flare Stacks
6.9 Steam Generation
6.10 Steam Use
6.11 Water Sources and Uses
   6.11.1 Water Quality Indicators
6.12 Recirculated Cooling Water from Cooling Towers
6.13 Sea Water Cooling
6.14 Air Cooling
6.15 Refrigeration
6.16 Electricity Demand and Supply
6.17 Distribution and Use of Electricity
6.18 Compressed Air
6.19 Inert Gas
6.20 Vacuum
6.21 Concluding Remarks

7 Energy Conservation
1 Introduction
2 Energy Consumption in Compression of Gases
   7.2.1 Process Specification for Gas Compressors
   7.2.2 Machine Selection
   7.2.3 Thermodynamics of Gas Compression
   7.2.4 Limits to Compression Ratio per Stage of Compression
   7.2.5 Intercooling of Gas during Compression
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.2.6 Reliability</td>
<td>138</td>
</tr>
<tr>
<td>7.2.7 Drives for Compressors</td>
<td>139</td>
</tr>
<tr>
<td>7.2.8 Energy Conservation in Gas Compression</td>
<td>139</td>
</tr>
<tr>
<td>7.3 Energy Consumption in Pumping of Liquids</td>
<td>139</td>
</tr>
<tr>
<td>7.3.1 Process Specification for Pumps</td>
<td>139</td>
</tr>
<tr>
<td>7.3.2 Power Requirement</td>
<td>141</td>
</tr>
<tr>
<td>7.3.3 Pump Machine Types</td>
<td>141</td>
</tr>
<tr>
<td>7.3.4 Centrifugal Pump Selection and Performance</td>
<td>142</td>
</tr>
<tr>
<td>7.3.5 Energy Conservation in Pumping of Liquids</td>
<td>144</td>
</tr>
<tr>
<td>7.4 Pressure Losses in Piping</td>
<td>144</td>
</tr>
<tr>
<td>7.4.1 Sizing of Pipes</td>
<td>144</td>
</tr>
<tr>
<td>7.5 Pressure Loss through Equipment</td>
<td>145</td>
</tr>
<tr>
<td>7.5.1 Heat Exchangers</td>
<td>145</td>
</tr>
<tr>
<td>7.5.2 Vapour–Liquid Contacting Columns</td>
<td>146</td>
</tr>
<tr>
<td>7.6 Agitation and Mixing</td>
<td>147</td>
</tr>
<tr>
<td>7.7 Heat Recovery</td>
<td>149</td>
</tr>
<tr>
<td>7.8 Energy Recovery from High Pressure Streams</td>
<td>150</td>
</tr>
<tr>
<td>7.9 Insulation</td>
<td>150</td>
</tr>
<tr>
<td>7.10 Plant Layout</td>
<td>151</td>
</tr>
<tr>
<td>7.11 Concluding Remarks</td>
<td>151</td>
</tr>
</tbody>
</table>

8 Materials Recycling

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1 Introduction</td>
<td>155</td>
</tr>
<tr>
<td>8.2 Recycling of Materials in Chemical Processes</td>
<td>155</td>
</tr>
<tr>
<td>8.2.1 Economics of Recycling Process Streams</td>
<td>156</td>
</tr>
<tr>
<td>8.2.2 Environmental Credits and Burdens of Recycling</td>
<td>156</td>
</tr>
<tr>
<td>8.3 Closed Loop and Open Loop Recycling</td>
<td>157</td>
</tr>
<tr>
<td>8.4 On-Site and Off-Site Recycling</td>
<td>159</td>
</tr>
<tr>
<td>8.4.1 Examples of Off-Site Recycling</td>
<td>159</td>
</tr>
<tr>
<td>8.5 Producer and Consumer Waste</td>
<td>159</td>
</tr>
<tr>
<td>8.6 Hierarchical Approach to Materials Recycling</td>
<td>160</td>
</tr>
<tr>
<td>8.7 Plastics Recycling</td>
<td>161</td>
</tr>
<tr>
<td>8.8 Glass Recycling</td>
<td>163</td>
</tr>
<tr>
<td>8.9 Recycling of Materials from Products</td>
<td>164</td>
</tr>
<tr>
<td>8.10 Waste Treatment Option</td>
<td>164</td>
</tr>
<tr>
<td>8.11 Aqueous Effluent Treatment and Water Recycling</td>
<td>165</td>
</tr>
<tr>
<td>8.12 Disposal of Wastes</td>
<td>167</td>
</tr>
<tr>
<td>8.12.1 Landfill</td>
<td>167</td>
</tr>
<tr>
<td>8.12.2 Incineration</td>
<td>168</td>
</tr>
<tr>
<td>8.13 Concluding Remarks</td>
<td>169</td>
</tr>
</tbody>
</table>
9 Waste Minimisation in Operations 171
  9.1 Non-Flow-Sheet Emissions from a Process Plant 171
  9.2 Plant Start-Up 172
    9.2.1 Case Example — Starting Up a Sulphuric Acid Plant 172
  9.3 Shut-Down of a Plant 173
  9.4 Abnormal Operation 173
  9.5 Plant Maintenance 174
  9.6 Cleaning of Plant and Equipment 175
  9.7 Fouling 175
  9.8 Transport and Storage of Raw Materials and Products 176
    9.8.1 Storage Tanks 177
    9.8.2 Major Environmental Incidents Arising from Storage 178
  9.9 Fugitive Emissions 179
  9.10 Environmental Risks Resulting from Storm Water 180
  9.11 Risks in Mining and Extraction of Materials 180
  9.12 Concluding Remarks 181

Problems: Part B 183

PART C: EVALUATION

10 Life Cycle Assessment 193
  10.1 Introduction 193
  10.2 Product and Process Applications 194
  10.3 Basic Steps in Life Cycle Assessment 196
  10.4 Goal Definition 197
    10.4.1 Example of System Boundary Determination 198
  10.5 Inventory Analysis 201
    10.5.1 Treatment of Utilities and Energy 202
    10.5.2 Allocation Procedures 202
  10.6 Example of Inventory Data Estimation 203
  10.7 Classification 205
    10.7.1 Further Discussion of Impact Categories 206
    10.7.2 Assignment and Weighting of Chemical Compounds 210
    10.7.3 Normalisation 215
  10.8 Improvement Analysis 215
  10.9 Some Challenges and Uncertainties in LCA 217
    10.9.1 Goal Definition 217
    10.9.2 Inventory Data 217
10.9.3 By-Products — Marketable or Waste? 219
10.9.4 Impact Analysis 219
10.9.5 Resource Depletion 220
10.9.6 Normalisation 221
10.9.7 Valuation 222
10.10 Some Alternative or Supplementary Approaches to LCA 224
  10.10.1 EPS System — An Example of Evaluation Used with Inventory Data 224
  10.10.2 Eco-Indicator 225
10.11 LCA Software 225
10.12 Concluding Remarks 225

11 Life Cycle Assessment Case Studies 229
  11.1 Introduction 229
  11.2 Life Cycle Inventories for Common Utilities 229
    11.2.1 Assumptions by Golonka and Burgess Regarding Utility Systems 230
    11.2.2 Derived Inventory Data 231
  11.3 Inventory Data for Distinct Electricity Supply Systems 231
  11.4 Hydrotreating of Diesel 233
    11.4.1 Hydrotreating Process 233
    11.4.2 System Boundary 233
    11.4.3 Inventory Data 235
    11.4.4 Impact Assessment 239
    11.4.5 Environmental Burden versus Benefit Comparison 242
    11.4.6 Conclusions 243

12 Safety Evaluation 247
  12.1 Introduction 247
  12.2 Importance of Learning from Accidents, Dangerous Occurrences 249
  12.3 Life Cycle Issues 251
  12.4 Health, Safety, and the Environment 252
  12.5 Examples of Safety Incidents in the Process Industries Involving Environmental Damage 253
  12.6 Accident Prevention 255
    12.6.1 The HAZOP Approach 255
  12.7 Techniques for Investigating Probability of Major Incidents 256
  12.8 Risk Assessment 257
14.3 Cost Benefit Approach to Enviro-Economic Assessment 299
14.4 Quantifying Benefits and Burdens 300
14.5 Case Examples in Enviro-Economic Assessment 300
  14.5.1 Case 1: Sulphuric Acid Manufacture 300
  14.5.2 Case 2: Product Improvement through Hydrotreating of Diesel 302
  14.5.3 Case 3: Power Generation from Fossil Fuels: CCGT-NG versus ST-Br Coal 304
14.6 Environmental Effects of Scale of Production 307
14.7 Sustainability Assessment and Sustainability Metrics 308
  14.7.1 Case Study on Sustainability of Electricity Generation 309
14.8 Perception and Assessment of Risk 310
14.9 Scenario Analysis 313
14.10 Concluding Remarks 313

Problems: Part C 315

Part D: Implementation

15 Planning for Sustainable Process Industries 325
  15.1 Introduction 325
  15.2 Forecasting 325
  15.3 Scenario Development 326
  15.4 Technology Innovation 327
    15.4.1 Intensification 327
    15.4.2 Technology Diffusion 328
    15.4.3 Technology Evolution 328
    15.4.4 Rates of Change 329
  15.5 Transition to Renewable Feedstocks 329
  15.6 Site Selection for Process Plants 331
  15.7 Integration of Process Plants and Process Industries 333
  15.8 Distributed Manufacture 334
    15.8.1 Case of Aqueous Sodium Cyanide Production at the Point of Use 335
  15.9 Government Legislation 340
  15.10 Stakeholder Engagement 341
  15.11 Lifestyle Implications 341
16 Process Design and Project Development

16.1 Introduction
16.2 The Design Process
16.3 Process Flow Sheet Development
   16.3.1 Defining the Need
   16.3.2 Creating Plausible Solutions
   16.3.3 Screening of Alternatives
   16.3.4 Further Evaluation of Selected Options
   16.3.5 Optimisation and Scrutiny of Final Solution
16.4 Criteria for Process Flow Sheet Evaluation
   16.4.1 Technical Feasibility
   16.4.2 Capital Cost
   16.4.3 Operating Costs
   16.4.4 Safety
   16.4.5 Environmental
   16.4.6 Sustainability
   16.4.7 Reliability
   16.4.8 Operability
16.5 Process Flow Sheet Documentation
16.6 Piping and Instrumentation Diagram
16.7 Project Development
16.8 Acceptability Criteria for Projects
   16.8.1 Technical Requirements
   16.8.2 Economic Viability
   16.8.3 Safety
   16.8.4 Environmental
   16.8.5 Sustainability
16.9 Integrating Criteria Assessments
16.10 Concluding Remarks

17 Operations Management

17.1 Operational Phase of a Process Plant
17.2 Plant Maintenance
17.3 Environment Management Systems
   17.3.1 Commitment and Policy
   17.3.2 Planning
   17.3.3 Implementation
   17.3.4 Measurement and Evaluation
   17.3.5 Review and Continuous Improvement
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.4</td>
<td>Environment Improvement Plan</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17.4.1  Examples of EIPs</td>
<td></td>
</tr>
<tr>
<td>17.5</td>
<td>Responsible Care</td>
<td>375</td>
</tr>
<tr>
<td>17.6</td>
<td>Environmental Performance Monitoring</td>
<td>376</td>
</tr>
<tr>
<td>17.7</td>
<td>Emergency Response Planning</td>
<td>378</td>
</tr>
<tr>
<td>17.8</td>
<td>Sustainability Reporting</td>
<td>378</td>
</tr>
<tr>
<td>17.9</td>
<td>Emissions Reporting</td>
<td>379</td>
</tr>
<tr>
<td>17.10</td>
<td>Concluding Remarks</td>
<td>380</td>
</tr>
</tbody>
</table>

Problems: Part D

Index of Topics
Index of Cases
Index of Set Problems