

Edited by Efstratios N. Pistikopoulos,  
Michael C. Georgiadis, and Vivek Dua

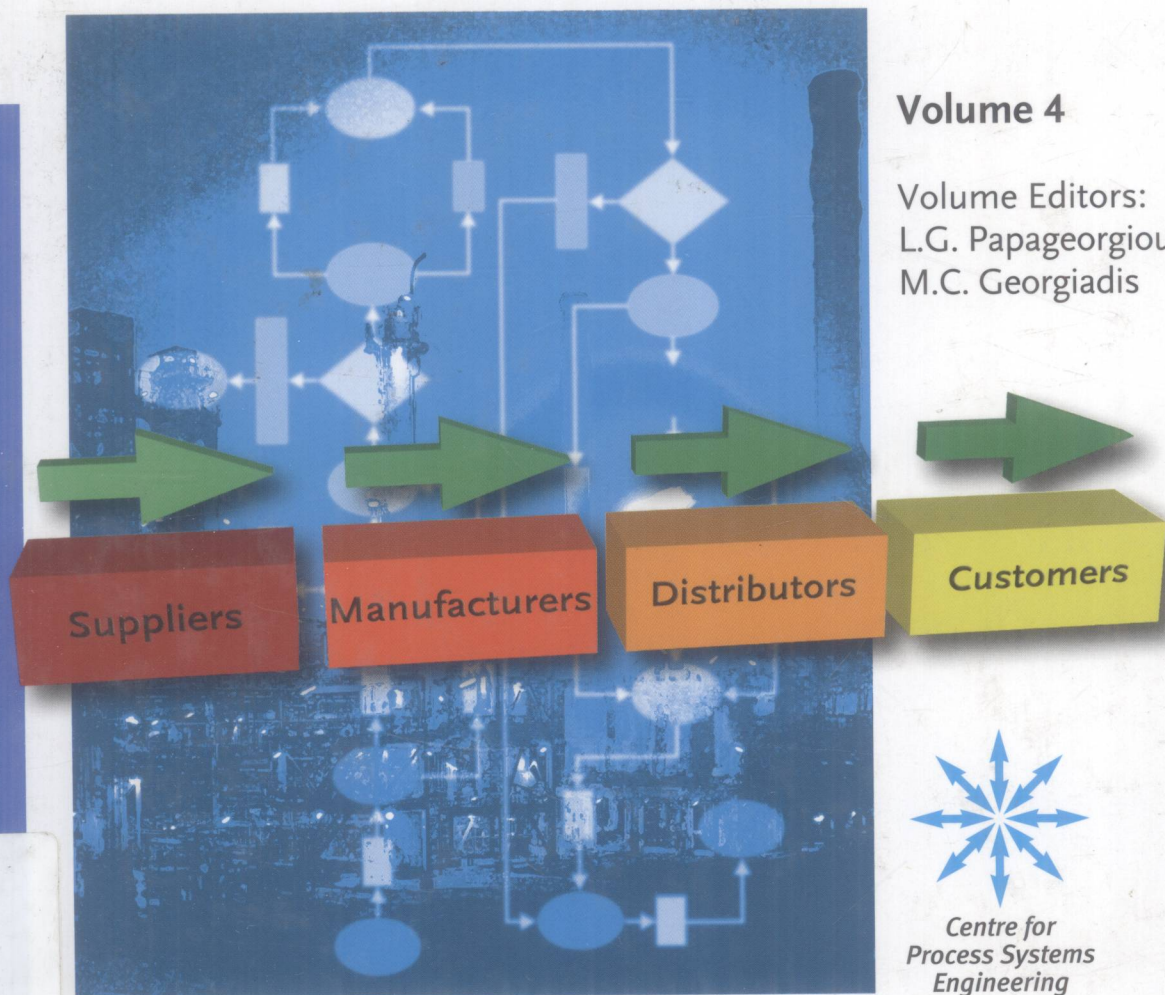
 WILEY-VCH

# Supply Chain Optimization

Part II

**Volume 4**

Volume Editors:  
L.G. Papageorgiou,  
M.C. Georgiadis



Centre for  
Process Systems  
Engineering

F274  
S959  
V.2

# Process Systems Engineering

*Edited by*

*Efstathios N. Pistikopoulos, Michael C. Georgiadis, and  
Vivek Dua*

Volume 4: Supply Chain Optimization, Part II

*Volume Edited by*

*Lazaros G. Papageorgiou and Michael C. Georgiadis*



WILEY-  
VCH



E2008001636

WILEY-VCH Verlag GmbH & Co. KGaA

## The Editors

### **Prof. Efstratios N. Pistikopoulos**

Centre for Process Systems Engineering  
Department of Chemical Engineering  
Imperial College London  
Roderic Hill Building  
South Kensington Campus  
London SW7 2AZ  
United Kingdom

### **Dr. Michael C. Georgiadis**

Centre for Process Systems Engineering  
Department of Chemical Engineering  
Imperial College London  
Roderic Hill Building  
London SW7 2AZ  
United Kingdom

### **Dr. Vivek Dua**

Centre for Process Systems Engineering  
Department of Chemical Engineering  
University College London  
London WC1E 7JE  
United Kingdom

### **Dr. Lazaros G. Papageorgiou**

Centre for Process Systems Engineering  
Department of Chemical Engineering  
University College London  
London WC1E 7JE  
United Kingdom

All books published by Wiley-VCH are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

### **Library of Congress Card No.:**

applied for

### **British Library Cataloguing-in-Publication Data**

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

### **Bibliographic information published by the Deutsche Nationalbibliothek**

Die Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <<http://dnb.d-nb.de>>.

© 2008 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form – by photoprinting, microfilm, or any other means – nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

**Typesetting** VTEX, Litauen

**Printing** Strauss GmbH, Mörlenbach

**Binding** Litges & Dopf buchbinderei GmbH, Heppenheim

**Cover Design** Grafik-Design Schulz, Fußgönheim

Printed in the Federal Republic of Germany  
Printed on acid-free paper

**ISBN:** 978-3-527-31906-0

## ***Related Titles***

Haber, R., Bars, R., Schmitz, U.

### **Predictive Control in Process Engineering**

approx. 400 pages with approx.  
150 figures  
2007  
Hardcover  
ISBN: 978-3-527-31492-8

Bröckel, U., Meier, W., Wagner, G. (eds.)

### **Product Design and Engineering Best Practices**

760 pages in 2 volumes with 355 figures and  
60 tables  
2007  
Hardcover  
ISBN: 978-3-527-31529-1

Engell, S. (ed.)

### **Logistic Optimization of Chemical Production Processes**

approx. 300 pages  
2007  
Hardcover  
ISBN: 978-3-527-30830-9

Ingham, J., Dunn, I. J., Heinzle, E.,  
Prenosil, J. E., Snape, J. B.

### **Chemical Engineering Dynamics An Introduction to Modelling and Computer Simulation**

640 pages with 474 figures and 4 tables  
2007  
Hardcover  
ISBN: 978-3-527-31678-6

Dimian, A. C., Bildea, C. S.

### **Chemical Process Design Computer-Aided Case Studies**

approx. 500 pages with approx. 450 figures  
2008  
Hardcover  
ISBN: 978-3-527-31403-4

Puigjaner, L., Heyen, G. (eds.)

### **Computer Aided Process and Product Engineering**

910 pages in 2 volumes with 281 figures  
and 77 tables  
2006  
Hardcover  
ISBN: 978-3-527-30804-0

Keil, F. J. (ed.)

### **Modeling of Process Intensification**

422 pages with 180 figures and 28 tables  
2007  
Hardcover  
ISBN: 978-3-527-31143-9

Agachi, P. S., Nagy, Z. K., Cristea, M. V.,  
Imre-Lucaci, A.

### **Model Based Control Case Studies in Process Engineering**

290 pages with 156 figures and 25 tables  
2007  
Hardcover  
ISBN: 978-3-527-31545-1

**Process Systems Engineering**

*Edited by*  
*Efstathios N. Pistikopoulos,*  
*Michael C. Georgiadis, and*  
*Vivek Dua*

**Volume 4**  
**Supply Chain Optimization, Part II**

*Volume Edited by*  
*Lazaros G. Papageorgiou and*  
*Michael C. Georgiadis*

## Preface – Volume 4: Supply Chain Optimization

Modern industrial enterprises are typically multiproduct, multipurpose, and multi-site facilities operating in different regions and countries and dealing with a global-wide international clientele. In such enterprise networks, the issues of global enterprise planning, coordination, cooperation and robust responsiveness to customer demands at the global as well as the local level are critical for ensuring effectiveness, competitiveness, business sustainability, and growth. In this context, it has long been recognized that there is a need for efficient integrated approaches that consider, in a systematic way, various levels of enterprise management, plant-wide coordination and plant operation, in order to reduce capital and operating costs, increase supply chain productivity and improve business responsiveness.

The supply chain concept has in recent years become one of the main approaches to achieve enterprise efficiency. The terminology implies that a system view is taken rather than a functional or hierarchical one. Enterprises cannot be competitive without considering supply chain activities. This is partially due to the evolving higher specialization in a more differentiated market. Most importantly, competition drives companies to reduced cost structures with lower inventories, more effective transportation systems, and transparent systems able to support information throughout the supply chain. A single company rarely controls the production of a commodity as well as sourcing, distribution, and retail.

Many typical supply chains today have production that spans several countries and product markets. The opportunities for supply chain improvements are large. Costs of keeping inventory throughout the supply chain to maintain high customer service levels are generally significant. There is a wide scope to reduce the inventory while still maintaining the high service standards required. Furthermore, the manufacturing processes can be improved so as to employ current working capital and labor more efficiently.

It has widely been recognized that enhanced performance of supply chains necessitates: (i) appropriate design of supply chain networks and its components and (ii) effective allocation of available resources over the network. Thus, in the last few years, there has been a multitude of efforts focused on providing improvements of supply chain management and optimization. These efforts include a wide range of models: from commercial enterprise resource planning systems and so-

called advanced planning systems to academic achievements (for example, linear and mixed-integer programming, multiagent systems).

Management of supply chains is a complex task mainly due to the large size of the physical supply network and inherent uncertainties. In a highly competitive environment, improved decisions are required for efficient supply chain management at strategic, tactical, and operational levels with time horizons ranging from several years to a few days, respectively. Depending on the level, one or more of the following decisions are taken:

- Number, size and location of manufacturing sites, warehouses and distribution centers.
- Network connectivity (e.g., allocation of suppliers to plants, warehouses to markets, etc.).
- Production decisions related to plant production planning and scheduling.
- Management of inventory levels and replenishment policies.
- Transportation decisions concerning mode of transportation (e.g., road, rail, etc.) and also size of material shipment.
- Sustainability aspects (e.g., environmental impact considerations, recycling policies, etc.).

Most of the above challenging research issues are addressed in Volumes 3 and 4 of this book series.

Volume 4 provides a comprehensive review of key research contributions concerning tactical and operational decisions of supply chain problems for the process industries.

Sousa, Shah, and Papageorgiou in Chapter 1 address a systematic optimization-based supply chain planning model of large process industrial companies of products with a high added value per mass unit. Here, transportation costs have a reduced impact in the total expenditure in supply chain activities, from raw material supply until distribution to final markets. A case study relevant to the pharmaceutical industry is presented concerning production allocation to manufacturing sites in a worldwide network. Both deterministic and stochastic cases are addressed and compared. The large, mixed-integer linear programming (MILP) models generated were efficiently solved using a temporal decomposition algorithm.

Dondo, Méndez, and Cerda in Chapter 7 consider an MILP-based mathematical formulation focused on the operational level of multiple vehicle pickup and delivery problems with time windows commonly arising in multisite systems. The proposed two-index model can be solved using a branch-and-cut commercial package to find the best vehicle routes and schedules for moderate-size problems. The formulation has been generalized to also consider pure pickup and delivery nodes, heterogeneous vehicles, multiple depots, as well as many-to-many transportation requests. To tackle medium-size problems, several preordering and variable and constraint elimination rules are introduced. Optimal solutions for a variety of benchmark problems featuring different sizes in terms of customer requests and vehicles, distinct cluster/random pickup and delivery locations and a range of time-window width distributions are reported.

Pratikakis, Realff, and Lee in Chapter 3, present a real-time approximate dynamic programming approach for the efficient solution of multistage supply chain decision problems under a stochastic environment. The supply chain system experiences stochastic variations in demand and price of the main products which are modeled using Markov chains. The main idea of the overall methodology is to start with a heuristic policy derived from an MILP formulation and to gradually construct a superior quality solution by interacting with the stochastic system via simulation.

Disruptions could bring about adverse effects such as blockage of material, information, and finance flows, loss of production, off-spec products, loss of efficiency, under- or oversupply, etc. Any of these could result in operational problems, loss of business opportunities, and financial losses. A deviation between plan and actual realization occurs during disruptions. Depending on the magnitude of the deviation, the necessary response would have to differ. Adhitya, Srinivasan, and Karimi in Chapter 4 first describe the crude oil supply chain and clearly state the rescheduling problem. Two new rescheduling methods are then presented to address supply chain disruptions. A petroleum refinery supply chain is used to identify the salient characteristics of the problem and review solution methods.

The group of Bandoni and coworkers in Chapter 5 propose a detailed and complete tactical planning model to aid in the negotiation instance of a typical large company that operates several nodes of the fruit industry supply chain. The proposed linear programming model considers the many interactions of the real network and the typical operative practices of the business. A real-world case study from the pip fruit industry of Argentina is used to illustrate the applicability of the proposed model.

The research area of batch and continuous process scheduling has received great attention from both academia and industry in the past two decades. This is motivated by the increasing pressure to improve efficiency and reduce costs, and by the significant advances in relevant modeling and solution techniques and the rapidly growing computational power. Shaik and Floudas in Chapter 6 present a comprehensive overview of the recent developments in scheduling of multiproduct, multipurpose batch, and continuous processes. Different continuous-time based scheduling models from the literature are discussed, followed by a comparative study of these methods on some benchmark examples.

Jia and Ierapetritou in Chapter 7 address the problem of refinery scheduling under uncertainty through a multiobjective optimization and a parametric integer linear programming approach. Several case studies considering the optimal operations of crude oil unloading and mixing, and gasoline blending and distributions are presented to illustrate the importance of considering uncertainty in demand in refinery scheduling operations.

Westerlund and coworkers in Chapter 8 present an MILP-based tool for the production and intermediate planning in the tissue manufacturing industry. The tool is based on a mixed-time scheduling formulation, implementing tailored software architecture as an access point to various information systems at the mill. The tool is furthermore integrated into a user-friendly interface and is concerned with the



production and raw material cost minimization, as well as intermediate storage utilization at the stock preparation section.

Sung and Maravelias in Chapter 9 provide a review of the methods that have been proposed for the solution of production planning problems in the chemical industry. First, the classical formulations used in Operations Research and the main software tools currently used in practice are discussed. Second, modeling approaches and optimization strategies for the integration of production planning with scheduling are presented. Finally, a brief discussion of specific applications and the integration of production planning with other models is analyzed.

In the final chapter, Ydstie and coworkers study inventory and control flows in complex supply chains using approaches developed in the area of process control. New methods for inventory control are introduced using frequency response analysis and an approach for feedback scheduling of assembly, disassembly, and repackaging lines is investigated. Furthermore, a method for control is developed which optimizes the intrinsic value of a business by managing inventory and flows so that costs are minimized.

This collection represents a set of stand-alone works that captures recent research trends in the development and application of techniques, methodologies, algorithms, and tools for optimizing various aspects of supply chain systems. We hope that by the end of the book, the reader will have developed a commanding comprehension of the main aspects of integrated supply chains, the ability to critically access the key characteristics and elements related to the design and operation of supply chains, and the capacity to implement the new technology in practice.

We are extremely grateful to the authors for their outstanding contributions and for their patience, which have led to a final product that far exceeded our expectations.

London, June 2007

*L. G. Papageorgiou*

*M. C. Georgiadis*

## List of Authors

### ***Arief Adhitya***

Institute of Chemical and Engineering  
Sciences  
1 Pesek Road, Jurong Island  
Singapore 627833  
Singapore

### ***Professor José A. Bandoni***

Planta Piloto de Ingeniería Química  
PLAPIQUI (UNS–CONICET)  
Camino La Carrindanga, Km. 7  
8000 Bahía Blanca  
Argentina

### ***Aníbal M. Blanco***

Planta Piloto de Ingeniería Química  
PLAPIQUI (UNS–CONICET)  
Camino La Carrindanga, Km. 7  
8000 Bahía Blanca  
Argentina

### ***Dr. Jaime Cerdá***

INTEC (UNL–CONICET)  
Güemes 3450  
3000 Santa Fe  
Argentina

### ***Dr. Rodolfo Dondo***

INTEC (UNL–CONICET)  
Güemes 3450  
3000 Santa Fe  
Argentina

### ***Eduardo J. Dozal-Mejorada***

Carnegie Mellon University  
Department of Chemical Engineering  
5000 Forbes Avenue  
Pittsburgh, PA 15213-3890  
USA

### ***Professor Christodoulos A. Floudas***

Princeton University  
Department of Chemical Engineering,  
Princeton  
New Jersey 08544  
USA

### ***Mattias Hästbacka***

Åbo Akademi University  
Centre for Industrial Engineering and  
Management  
Faculty of Technology  
FI-20500 ÅBO  
Finland

### ***Professor Marianthi G. Ierapetritou***

The State University of New Jersey  
Department of Chemical and  
Biochemical Engineering  
Rutgers University  
Piscataway, NJ 08854  
USA

**Zhenya Jia**

The State University of New Jersey  
Department of Chemical and  
Biochemical Engineering  
Rutgers University  
Piscataway, NJ 08854  
USA

**Kendell R. Jillson**

Carnegie Mellon University  
Department of Chemical Engineering  
5000 Forbes Avenue  
Pittsburgh, PA 15213-3890  
USA

**Jarkko Kaplin**

Metsa-Tissue Corporation  
S-54288 Mariestad  
Sweden

**Professor Iftekhar A. Karimi**

Department of Chemical and  
Biomolecular Engineering  
National University of Singapore  
4 Engineering Drive 4  
Singapore 117576  
Singapore

**Professor Jay H. Lee**

Georgia Institute of Technology  
School of Chemical & Biomolecular  
Engineering  
311 Ferst Drive  
N.W. Atlanta, GA 30332-0100  
USA

**Professor Christos T. Maravelias**

Department of Chemical and Biological  
Engineering  
University of Wisconsin – Madison  
Madison, WI 53706  
USA

**Guillermo L. Masini**

Universidad Nacional del Comahue  
Mechanical Engineering Department  
Engineering Faculty  
Buenos Aires 14000  
8300 Neuquén,  
Argentina

**Dr. Carlos A. Méndez**

INTEC (UNL-CONICET)  
Güemes 3450  
3000 Santa Fe  
Argentina

**Dr. Lazaros G. Papageorgiou**

University College London  
Centre for Process Systems Engineering  
Department of Chemical Engineering  
Torrington Place  
London WC1 7JE  
UK

**Noemí C. Petracci**

Planta Piloto de Ingeniería Química  
PLAPIQUI (UNS-CONICET),  
Camino La Carrindanga, Km. 7  
8000 Bahía Blanca  
Argentina

**Nikolaos E. Pratikakis**

Georgia Institute of Technology  
School of Chemical & Biomolecular  
Engineering,  
311 Ferst Drive  
N.W. Atlanta, GA 30332-0100  
USA

**Professor Matthew J. Realff**

Georgia Institute of Technology  
School of Chemical & Biomolecular  
Engineering  
311 Ferst Drive  
N.W. Atlanta, GA 30332-0100  
USA

**Professor Nilay Shah**

Imperial College London  
 Centre for Process Systems Engineering  
 Department of Chemical Engineering  
 South Kensington Campus  
 London SW7 2AZ  
 UK

**Munawar A. Shaik**

Indian Institute of Technology  
 Department of Chemical Engineering  
 Delhi  
 Hauz Khas  
 New Delhi – 110 016  
 India

**Dr. Rui T. Sousa**

Imperial College London  
 Centre for Process Systems Engineering  
 Department of Chemical Engineering  
 South Kensington Campus  
 London SW7 2AZ  
 UK

**Professor Rajagopalan Srinivasan**

Institute of Chemical and Engineering  
 Sciences  
 1 Pesek Road, Jurong Island  
 Singapore 627833  
 Singapore  
 and  
 National University of Singapore  
 Departement of Chemical &  
 Biomolecular Engineering  
 4 Engineering Drive 4  
 Singapore 117576  
 Singapore

**Charles Sung**

Department of Chemical and Biological  
 Engineering  
 University of Wisconsin – Madison  
 Madison, WI 53706  
 USA

**Dr. Joakim Westerlund**

Åbo Akademi University  
 Centre for Industrial Engineering and  
 Management  
 Faculty of Technology  
 FI-20500 ÅBO  
 Finland

**Professor Tapio Westerlund**

Åbo Akademi University  
 Centre for Industrial Engineering and  
 Management  
 Process Design Laboratory  
 FI-20500 Turku  
 Finland

**Professor B. Erik Ydstie**

Carnegie Mellon University  
 Department of Chemical Engineering  
 5000 Forbes Avenue  
 Pittsburgh, PA 15213-3890  
 USA

## Contents

<b>Preface – Volume 4: Supply Chain Optimization</b>	<b>XIII</b>
<b>List of Authors</b>	<b>XVII</b>

<b>1</b>	<b>Supply Chains of High-Value Low-Volume Products</b>	<b>1</b>
	<i>R. Sousa, N. Shah, L. G. Papageorgiou</i>	<i>1</i>
1.1	Introduction	1
1.1.1	Pharmaceutical Industry	3
1.2	Literature on Supply-Chain Modeling and Optimization	4
1.2.1	Case Studies	4
1.2.2	Deterministic Studies	6
1.2.3	Case Study Part I: Problem Statement	9
1.3	Stochastic Models	11
1.3.1	Stochastic Programming with Recourse	12
1.3.2	Stochastic Dynamic Programming (for Optimal Control)	13
1.3.3	Works in Planning Optimization Under Uncertainty	13
1.3.3.1	Stochastic Programming, Probability-Based Approach	13
1.3.3.2	Stochastic Programming, Scenario-Based Approach	14
1.3.3.3	Stochastic Dynamic Programming Approach	16
1.3.4	Case Study Part II: Planning Under Uncertainty	16
1.3.4.1	Scenarios	17
1.4	Solution Algorithms	18
1.4.1	Decomposition and Hierarchical Algorithms	18
1.4.2	Hybrid Methods	20
1.4.2.1	Lagrangian Decomposition	20
1.4.2.2	Genetic Algorithms	21
1.4.3	Case Study Part III: Solution Methodology	22
1.4.3.1	Solution Algorithm Performance	22
1.4.3.2	Financial Risk	24
1.4.3.3	Comments	24
1.5	Summary	25

<b>2</b>	<b>Solving Multiple Vehicle Pickup and Delivery Problems in Multisite Systems by a Rigorous Optimization Approach</b>	<b>29</b>
	<i>R. Dondo, C. A. Méndez, J. Cerdá</i>	29
2.1	Introduction	30
2.1.1	Previous Heuristic Approaches	31
2.1.2	Exact Optimization Methods	32
2.2	The Problem Definition	34
2.3	The Problem Mathematical Formulation	35
2.3.1	The Problem Constraints	36
2.3.1.1	Assignment Constraints	36
2.3.1.2	Routing-Cost Defining Constraints	37
2.3.1.3	Arrival-Time Defining Constraints	39
2.3.1.4	Vehicle-Load Defining Constraints	40
2.3.2	The Problem Objective Function	43
2.4	Time Window-Based Variable and Constraint Elimination Rules	43
2.4.1	Preassigning Vehicles to Transportation Requests	45
2.5	Numerical Results and Discussion	46
2.6	Conclusions	56
<b>3</b>	<b>A Real Time Approximate Dynamic Programming Approach: A High Dimensional Supply Chain Application</b>	<b>61</b>
	<i>N. E. Pratikakis, M. J. Realff, H. Lee</i>	61
3.1	Introduction	61
3.1.1	Chapter Structure	63
3.2	Dynamic Programming	63
3.2.1	The Value Function	63
3.2.2	Markov Decision Processes	64
3.2.3	From Value Iteration to Asynchronous Value Iteration to Real-Time Dynamic Programming	65
3.2.4	A Review Of Approximate Dynamic Programming Techniques	66
3.2.4.1	Minimizing the COD Concerning $ \mathbb{S} $	66
3.2.4.2	Minimizing the COD Concerning $ \mathbb{A} $	67
3.2.4.3	Minimizing the COD Concerning the Expectation Operator	68
3.2.4.4	Value Function Approximators	68
3.3	A High-Dimensional Supply Chain Case Study	69
3.3.1	Introduction	69
3.3.2	Mathematical Modelling of the Supply Chain	70
3.3.3	Sets	70
3.3.4	Material Balances at Each Tank	70
3.3.4.1	Constraints on $y_{T,C,(P_m)}(t)$	71
3.3.5	Reaction and Separation Processes – The Determination of $Pr_{u,p}(t)$	73
3.3.5.1	Reaction Processes	73
3.3.5.2	Separation Processes	74

3.3.5.3	Hard Constraints	74
3.3.6	Decision Variables	75
3.3.7	Objective Function	75
3.3.7.1	Net Profit $p(t)$	75
3.3.7.2	Net Cost $c(t)$	75
3.4	Formulating the Problem as an MDP	76
3.4.1	State Variables	76
3.4.2	Decision Variables	76
3.4.3	Transition Function	76
3.4.4	Objective Function	77
3.4.5	Concluding Remarks	77
3.5	A Real-Time Approximate Dynamic Programming Algorithm	78
3.5.1	The Greedy RTADP Algorithm	79
3.5.2	Key Elements of $A_{\text{sub}}$	80
3.5.3	On Calculating $J_i^{\pi}(s_i)$	81
3.6	Simulation Results	82
3.6.1	Simulation Procedure	83
3.6.2	Performance Comparison	84
3.7	Conclusions	86
<b>4</b>	<b>Robust Supply-Chain Operations through Rescheduling</b>	<b>89</b>
	<i>A. Adhitya, R. Srinivasan, I. A. Karimi</i>	89
4.1	Introduction	89
4.2	Refinery Supply Chain	91
4.3	Rescheduling Problem Statement	92
4.3.1	Literature Review	95
4.4	Rescheduling Methodologies	96
4.4.1	Heuristic-Based Rescheduling	96
4.4.2	Model-Based Rescheduling	98
4.5	Case Study	105
4.6	Discussions	117
<b>5</b>	<b>Supply Chain Tactical Optimization in the Fruit Industry</b>	<b>121</b>
	<i>G. L. Masini, A. M. Blanco, N. Petracci, J. A. Bandoni</i>	121
5.1	Introduction	122
5.2	Literature Review	124
5.3	Fruit Industry Supply Chain Description	126
5.3.1	Farms	126
5.3.2	Packaging Plants	126
5.3.3	Cold Storage	127
5.3.4	Fruit Reception Sites	127
5.3.5	Milling Plants	127
5.3.6	Concentrated Juice Plants	127

5.3.7	Cider Plants	128
5.3.8	Clients	128
5.3.9	Third Party Suppliers and Customers	128
5.3.10	Transportation	128
5.3.11	Global FISC Operations	128
5.3.12	Tactical Model Scope	129
5.4	Mathematical Programming Model	130
5.4.1	Fruit Production in Farms	130
5.4.2	Allocation of Fresh Fruit from Own Farms	131
5.4.3	Fruit Reception at PPs	132
5.4.4	Fruit Processing at PPs	132
5.4.5	Waste Fruit from PPs	132
5.4.6	Packed Fruit from PPs and TPSs	133
5.4.7	Fruit Balance at CSFs	133
5.4.8	Fruit Balance at FRs	134
5.4.9	Fruit Balance at MPs	135
5.4.10	Raw Material Reception at CJs	135
5.4.11	Fruit Processing at CJs	136
5.4.12	Juice Storage at CJs	136
5.4.13	Raw Material Reception at CPs	136
5.4.14	Fruit Processing at CPs	137
5.4.15	Packed Fruit Delivery to Clients	137
5.4.16	Concentrated Juice Delivery to Clients	137
5.4.17	Third Party Material Availability	137
5.4.18	Product Delivery Constraints	138
5.4.19	Raw Material Costs	139
5.4.20	Final Products Purchase Cost	140
5.4.21	Transportation Costs	140
5.4.22	Cold Storage Cost (Third Party Rental)	143
5.4.23	Operating Costs	143
5.4.24	Sales Income	144
5.4.25	Cold Storage Capacity Rental Income	145
5.4.26	Objective Function	145
5.4.27	Company Supply Chain Optimization Problem	145
5.5	Results and Discussion	145
5.6	Conclusions and Future Work	154
<b>6</b>	<b>Short-Term Scheduling of Batch and Continuous Processes</b>	<b>173</b>
	<i>M. A. Shaik, Ch. A. Floudas</i>	173
6.1	Classification of Scheduling Formulations	173
6.1.1	Time Representation	173
6.1.2	Characteristics of Process Scheduling Problems	175
6.1.2.1	Processing Sequences	175
6.1.2.2	Processing Modes of Operation	176



6.1.2.3	Intermediate Storage Policies	176
6.1.2.4	Demand Patterns	177
6.1.2.5	Resource Considerations	177
6.1.2.6	Changeovers	177
6.1.2.7	Performance Criteria	177
6.2	Short-Term Scheduling of Batch Processes	177
6.2.1	Unit-Specific Event-Based Model of Ierapetritou and Floudas [29] (I&F)	178
6.2.2	Global Event-Based Model of Castro and coworkers [21, 22]	179
6.2.3	Global Event-Based Model of Maravelias and Grossmann [28] (M&G)	181
6.2.4	Slot-Based Model of Sundaramoorthy and Karimi [10] (S&K)	183
6.2.5	Computational Studies	185
6.2.5.1	Example 1	185
6.2.5.2	Example 2	188
6.2.5.3	Example 3	189
6.3	Short-Term Scheduling of Continuous Processes	195
6.3.1	Unlimited Intermediate Storage	197
6.3.1.1	Allocation Constraints	197
6.3.1.2	Capacity Constraints for Processing Tasks	197
6.3.1.3	Material Balances	197
6.3.1.4	Demand Constraints	198
6.3.1.5	Duration Constraints for Processing Tasks	199
6.3.1.6	Sequencing Constraints	199
6.3.1.7	Extra Tightening Constraint	201
6.3.2	Dedicated Finite Intermediate Storage with Storage Bypassing Allowed	201
6.3.2.1	Storage Bypassing Allowed	201
6.3.3	No Intermediate Storage	202
6.3.4	Flexible Finite Intermediate Storage with Storage Bypassing Allowed	202
6.3.4.1	Allocation Constraints for Storage Tasks	203
6.3.4.2	Capacity Constraints for Storage Tasks	203
6.3.4.3	Material Balances	203
6.3.4.4	Duration Constraints for Storage Tasks	204
6.3.4.5	Sequencing Constraints. Different Tasks in Different Units for Storage Tasks	204
6.3.5	Dedicated and Flexible Finite Intermediate Storage without Storage Bypassing	205
6.3.5.1	Dedicated-Finite-Intermediate-Storage Case without Bypassing of Storage	205
6.3.5.2	Flexible-Finite-Intermediate-Storage Case without Bypassing of Storage	206
6.3.6	Computational Study	207
6.3.6.1	Example 4	207