Port Automation and Vehicle Scheduling

Advanced Algorithms for Scheduling Problems of AGVs

THIRD EDITION

Hassan Rashidi
Edward P. K. Tsang
Container terminals are constantly being challenged to adjust their throughput capacity to match fluctuating demand. Examining the optimization problems encountered in today's container terminals, *Port Automation and Vehicle Scheduling: Advanced Algorithms for Scheduling Problems of AGVs, Third Edition* provides advanced algorithms for handling the scheduling of Automated Guided Vehicles (AGVs) in ports.

Building on the earlier editions, previously titled *Vehicle Scheduling in Port Automation: Advanced Algorithms for Minimum Cost Flow Problems*, this book has undergone extensive revisions and includes two new chapters. New material addresses the solutions to the modeling of decisions in Chapter 3, while in Chapter 11 the authors address an emerging challenge in automated container terminals with integrated management.

**Key Features:**

- Classifies the optimization problems of the ports into five scheduling decisions. For each decision, it supplies an overview, formulates each of the decisions as constraint satisfaction and optimization problems, and then covers possible solutions, implementation, and performance.
- Explores in Part One of the book the various optimization problems in modern container terminals, while details in Part Two advanced algorithms for the minimum cost flow (MCF) problem and for the scheduling problem of AGVs in ports.
- Offers complete package that can help readers address the scheduling problems of AGVs in ports.

This is a valuable reference for port authorities and researchers, including specialists and graduate students in operation research. For specialists, it provides novel and efficient algorithms for network flow problems. For students, it supplies the most comprehensive survey of the field along with a rigorous formulation of the problems in port automation.
Port Automation and Vehicle Scheduling
Advanced Algorithms for Scheduling Problems of AGVs
Third Edition

Hassan Rashidi
Edward P. K. Tsang

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the Taylor & Francis Group, an Informa business
Contents

List of Figures .............................................................................................................. xi
List of Tables ............................................................................................................... xv
List of Abbreviations ................................................................................................... xix
Preface ........................................................................................................................... xxix
Acknowledgments ....................................................................................................... xxiii
Authors ......................................................................................................................... xxv

1 Introduction ............................................................................................................... 1
  1.1 Objectives ............................................................................................................. 1
    1.1.1 Optimization in Ports ................................................................................... 2
    1.1.2 Scheduling of AGVs and Development of Advanced Algorithms ........ 7
  1.2 Structure of Subsequent Chapters ...................................................................... 8

PART 1 OPTIMIZATION PROBLEMS FACING MODERN CONTAINER TERMINALS

2 Problems in Container Terminals ........................................................................ 13
  2.1 Compartments ..................................................................................................... 13
  2.2 Operations .......................................................................................................... 15
  2.3 Decisions to Be Made ......................................................................................... 17
    2.3.1 Allocation of Berths to Arriving Vessels and QCs to Docked Vessels .... 18
    2.3.2 Storage Space Assignment .......................................................................... 20
    2.3.3 Rubber Tyred Gantry Crane Deployment ................................................. 20
    2.3.4 Scheduling and Routing of Vehicles ......................................................... 20
    2.3.5 Appointment Times to XTs ........................................................................ 20

3 Formulations of the Problems ............................................................................. 21
  3.1 Allocation of Berths to Arriving Vessels and Quay Cranes to Docked Vessels ... 22
    3.1.1 Assumptions ................................................................................................. 26
3.1.2 Decision Variables and Domains ................................................. 30
3.1.3 Constraints............................................................................. 31
3.1.4 Objective Function................................................................. 32

3.2 Storage Space Assignment .......................................................... 32
3.2.1 Assumptions........................................................................... 36
3.2.2 Decision Variables and Domains ............................................ 41
3.2.3 Constraints............................................................................. 42
3.2.4 Objective Function................................................................. 44

3.3 Rubber Tyred Gantry Crane Deployment ...................................... 44
3.3.1 Assumptions........................................................................... 47
3.3.2 Decision Variables and Domains ............................................ 51
3.3.3 Constraints............................................................................. 51
3.3.4 Objective Function................................................................. 52

3.4 Scheduling and Routing of Vehicles............................................. 53
3.4.1 Assumptions........................................................................... 57
3.4.2 Decision Variables and Domains ............................................ 61
3.4.3 Constraints............................................................................. 61
3.4.4 Objective Function................................................................. 63

3.5 Appointment Times to eXternal Trucks........................................ 63
3.5.1 Assumptions........................................................................... 67
3.5.2 Decision Variables and Domains ............................................ 68
3.5.3 Constraints............................................................................. 68
3.5.4 Objective Function................................................................. 68

3.6 Container Terminals over the World: A Survey ............................. 69
3.7 Summary and Conclusion.............................................................. 69

4 Solutions to the Decisions: Review and Suggestions ......................... 73
4.1 Simulation of Container Terminals ................................................. 74
4.2 Selecting an Architecture............................................................... 78
4.3 Classification of Scheduling Methods............................................ 79
4.4 Frameworks for Optimization and Scheduling Problems...................... 80
4.5 Solution Methods for Vehicle Problems, Developed
before 2000 ............................................................................. 85
4.6 Solution Methods for Vehicle Problems, Developed in the
Twenty-First Century .................................................................. 91
4.7 Suggestions for How to Do the Simulation .................................... 98
4.7.1 Microscopic Simulation............................................................. 98
4.7.1.1 Entities............................................................................ 98
4.7.1.2 Resources....................................................................... 99
4.7.1.3 Control Elements............................................................. 100
4.7.1.4 Operations ................................................................... 100
4.7.2 Macroscopic Simulation........................................................... 101
4.7.2.1 Agent-Based Simulation (ABS) ......................................... 101
4.7.2.2 Object-Based Simulation (OBS) ....................................... 101
PART 2  ADVANCED ALGORITHMS FOR THE SCHEDULING
PROBLEM OF AUTOMATED GUIDED VEHICLES

5   Vehicle Scheduling: A Minimum Cost Flow Problem ...............109
5.1 Reasons to Choose This Problem ......................................109
5.2 Assumptions .................................................................110
5.3 Variables and Notations ....................................................114
5.4 The Minimum Cost Flow Model ........................................117
  5.4.1 Graph Terminology ....................................................117
  5.4.2 The Standard Form of the Minimum Cost Flow Model ....117
  5.4.3 Applications of the Minimum Cost Flow Model .............119
5.5 The Special Case of the MCF Model for Automated
Guided Vehicles Scheduling ................................................120
  5.5.1 Nodes and Their Properties in the Special Graph ..........121
  5.5.2 Arcs and Their Properties in the Special Graph ............122
  5.5.3 The MCF-AGV Model for the Automated Guided
      Vehicles Scheduling ....................................................124
5.6 Summary and Conclusion ................................................126

6   Network Simplex: The Fastest Algorithm ............................127
6.1 Reasons to Choose NSA ..................................................127
6.2 The Network Simplex Algorithm .......................................128
  6.2.1 Spanning Tree Solutions and Optimality Conditions ......128
  6.2.2 The Algorithm NSA ..................................................131
  6.2.3 The Difference between NSA and Original Simplex ......133
  6.2.4 A Literature over Pricing Rules ................................133
  6.2.5 Strongly Feasible Spanning Tree ................................135
6.3 Simulation Software .......................................................136
  6.3.1 The Features of Our Software ....................................136
  6.3.2 The Implementation of NSA in Our Software ...............139
  6.3.3 How the Program Works ..........................................140
  6.3.4 The Circulation Problem .........................................144
6.4 Experimental Results ......................................................145
6.5 An Estimate of the Algorithm’s Complexity in Practice .........148
6.6 Limitation of the NSA in Practice ....................................151
6.7 Summary and Conclusion ................................................151

7   Network Simplex Plus: Complete Advanced Algorithm ..........153
7.1 Motivations ....................................................................153
7.2 The Network Simplex Plus Algorithm (NSA+) ......................154
7.2.1 Anti-Cycling in NSA+ .............................................................. 154
7.2.2 Memory Technique and Heuristic Approach
    in NSA+ ...................................................................................... 154
7.2.3 The Differences between NSA and NSA+ ......................... 155
7.3 A Comparison between NSA and NSA+ .................................. 156
7.4 Statistical Test for the Comparison ....................................... 159
7.5 Complexity of Network Simplex Plus Algorithm (NSA+) .... 160
7.6 Software Architecture for Dynamic Aspect ......................... 161
7.7 Experimental Results from the Dynamic Aspect ................. 163
7.8 Summary and Conclusion ...................................................... 165

8 Dynamic Network Simplex: Dynamic Complete Advanced
   Algorithm .................................................................................. 167
8.1 Motivations ............................................................................ 167
8.2 Classification of Graph Algorithms and Dynamic
    Flow Model ................................................................................ 168
8.3 The Dynamic Network Simplex Algorithm ......................... 171
8.3.1 Data Structures .................................................................. 171
8.3.2 Memory Management .......................................................... 175
8.3.3 The Algorithms DNSA and DNSA+ .................................. 175
8.4 Software Architecture for Dynamic Aspect ......................... 183
8.5 A Comparison between DNSA+ and NSA+ ......................... 185
8.6 Statistical Test for the Comparison ....................................... 186
8.7 Complexity of the Algorithm ............................................... 187
8.8 Summary and Conclusion ...................................................... 187

9 Greedy Vehicle Search: An Incomplete Advanced Algorithm .... 189
9.1 Motivations ............................................................................ 189
9.2 Problem Formalization ............................................................ 189
9.2.1 Nodes and Their Properties in the Incomplete Graph ...... 190
9.2.2 Arcs and Their Properties in the Incomplete Graph .............. 191
9.2.3 The Special Case of the MCF-AGV Model for
    Automated Guided Vehicles Scheduling ................................. 192
9.3 Algorithm Formalization .......................................................... 193
9.4 Software Architecture for Dynamic Aspect ......................... 193
9.5 A Comparison between GVS and NSA+ and Quality of the
    Solutions .................................................................................... 195
9.6 Statistical Test for the Comparison ....................................... 197
9.7 Complexity of Greedy Vehicle Search ................................. 198
9.7.1 Complexity of GVS for Static Problem ......................... 198
9.7.2 Complexity of GVS for Dynamic Problem ..................... 200
9.8 A Discussion over GVS and Meta-Heuristic ....................... 200
9.9 Summary and Conclusion ...................................................... 201
### 10 Multi-Load and Heterogeneous Vehicles Scheduling: Hybrid Solutions

10.1 Motivation ................................................................. 203
10.2 Assumptions and Formulation ................................................ 204
  10.2.1 Assumptions ................................................................. 204
  10.2.2 Formulation ................................................................. 205
  10.2.3 Decision Variable ............................................................ 205
  10.2.4 Constraints and Objective Function ...................................... 205
10.3 Solutions to the Problem ....................................................... 207
  10.3.1 Simulated Annealing Method for the Multi-Load AGVs ............... 207
  10.3.2 The Hybrid of SAM and NSA for Heterogeneous AGVs ............... 208
10.4 Experimental Results ......................................................... 209
10.5 Summary and Conclusion ................................................... 211

### 11 Integrated Management of Equipment in Automated Container Terminals

11.1 Introduction ................................................................. 213
11.2 Motivations ................................................................. 214
11.3 Related Works over Automated Container Terminals ....................... 216
11.4 Problem Description and Modeling .......................................... 221
  11.4.1 Complexity of the Problem ............................................... 221
  11.4.2 Problem Formulation ...................................................... 226
11.5 The Proposed Method ....................................................... 227
  11.5.1 Chromosome ................................................................. 228
  11.5.2 Crossover Operator ......................................................... 229
  11.5.3 Mutation Operator ............................................................ 231
11.6 Simulation and Evaluation of the Proposed Method ......................... 232
  11.6.1 Parameters ................................................................. 232
  11.6.2 Numerical Experiments ................................................... 234
11.7 Summary and Conclusions ................................................... 237

### 12 Conclusions and Future Research

12.1 Summary of This Research Done ........................................... 239
12.2 Observations and Conclusions ............................................... 242
12.3 Research Contributions ...................................................... 245
12.4 Future Research ............................................................. 246
  12.4.1 Scheduling and Routing of the Vehicles ................................... 247
  12.4.2 Economic and Optimization Model ....................................... 247
  12.4.3 Automated Container Terminal ........................................... 248
  12.4.4 The Next Generation of Container Terminal ............................... 249
Appendix: Information on Web ................................................................. 251
  Overview of This Research ............................................................... 252
  Assumptions .................................................................................... 252
  Development ...................................................................................... 253
  Some Interfaces of Our Software ...................................................... 254

References ........................................................................................... 257

Index ........................................................................................................ 271
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1</td>
<td>Container throughput at ports worldwide from 2012 to 2020 with a forecast for 2021 until 2024 (in million TEUs).</td>
<td>6</td>
</tr>
<tr>
<td>Figure 2.1</td>
<td>The container storage area in a port. See [131].</td>
<td>14</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>An RTGC sits across the width of a block. See [131].</td>
<td>14</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>Transfer of an RTGC between two blocks. See [215].</td>
<td>15</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>A typical Quay Crane. See [131].</td>
<td>16</td>
</tr>
<tr>
<td>Figure 2.5</td>
<td>A Straddle carrier (left) and an automated guided vehicle (right) while they are carrying a container. (SCs can load/unload and transport containers.)</td>
<td>16</td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>Park and Kim’s two phases scheduling of berths and cranes. See [143].</td>
<td>29</td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>An output of the berth and crane scheduling problem.</td>
<td>30</td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>Port’s layout with the primary and secondary storage types. See [184].</td>
<td>39</td>
</tr>
<tr>
<td>Figure 3.4</td>
<td>Cross over problem for two RTGCs in the storage area.</td>
<td>50</td>
</tr>
<tr>
<td>Figure 3.5</td>
<td>Flow of outbound containers (SA = storage area, QS = quayside).</td>
<td>64</td>
</tr>
<tr>
<td>Figure 3.6</td>
<td>Flow of inbound containers (SA = storage area, QS = quayside).</td>
<td>64</td>
</tr>
<tr>
<td>Figure 5.1</td>
<td>Layout of the container terminal.</td>
<td>111</td>
</tr>
<tr>
<td>Figure 5.2</td>
<td>Phenomena arising in scheduling and routing of AGVs. See [153].</td>
<td>112</td>
</tr>
<tr>
<td>Figure 5.3</td>
<td>Traveling time computations between the next location of vehicle and the next job.</td>
<td>115</td>
</tr>
<tr>
<td>Figure 5.4</td>
<td>Traveling time computations between job $i$ and job $j$.</td>
<td>116</td>
</tr>
<tr>
<td>Figure 5.5</td>
<td>An example of the MCF-AGV model for 2 AGVs and 4 jobs.</td>
<td>125</td>
</tr>
</tbody>
</table>
Figure 6.1  A feasible spanning tree solution (dotted) ................................................. 128
Figure 6.2  The Network Simplex Algorithm ................................................................. 131
Figure 6.3  An example of a strongly feasible spanning tree [See 3] ............................ 135
Figure 6.4  The main screenshot of the software ......................................................... 137
Figure 6.5  Relationships between the tables of the database ...................................... 139
Figure 6.6  Flowchart of Network Simplex Algorithm (Block pricing scheme) to select an entering arc ................................................................. 141
Figure 6.7  An example of the MCF-AGV model for 2 AGVs and 2 jobs in our software ........................................................................................................ 142
Figure 6.8  The input of the algorithm (NSA) in DIMACS (Centre for Discrete Mathematics and Theoretical Computer Science) format ................................................................. 143
Figure 6.9  The output of the algorithm (NSA) in DIMACS format .............................. 143
Figure 6.10  An example of the circulation problem (P = penalty) .............................. 144
Figure 6.11  CPU-Time required for solving the problem by Network Simplex Algorithm, based on the number of jobs ................................................................. 147
Figure 6.12  CPU-Time required for solving the problem by Network Simplex Algorithm, based on the number of arcs ................................................................. 148
Figure 7.1  Flowchart of network simplex plus algorithm to select an entering arc ........................................................................................................ 155
Figure 7.2  A comparison of CPU-Time required solving the same problems by NSA and NSA+ ................................................................. 158
Figure 7.3  The $t$-test acceptance and reject regions (NSA and NSA+H) ................. 159
Figure 7.4  Block diagram of the software and algorithm (NSA±) for dynamic aspect ........................................................................................................ 161
Figure 7.5  Operations of the software in dynamic aspect ........................................ 162
Figure 7.6  An experimental result from the dynamic scheduling problem of AGVs (NSA± solved the problem) ................................................................. 163
Figure 7.7  The attributes of the carried jobs in the dynamic scheduling problem of AGVs ........................................................................................................ 164
Figure 8.1  A sample of the spanning tree and its attributes (fix = ‘fixed’, ufd = ‘unfixed’). ........................................................................................................ 172
Figure 8.2  The dynamic network simplex algorithm ................................................. 177
Figure 8.3  The pseudo-code of reconstructing the spanning tree in dynamic network simplex algorithm ........................................... 178

Figure 8.4  The pseudo-code of removing a node from the spanning tree in dynamic network simplex algorithm ..................................... 178

Figure 8.5  The new spanning tree after removing nodes 8 (see Figure 8.1). ........................................................................ 179

Figure 8.6  The new spanning tree after removing node 3 (see Figure 8.1). ........................................................................ 180

Figure 8.7  The new spanning tree after removing node 4 (see Figure 8.6). ........................................................................ 181

Figure 8.8  The pseudo-code of inserting a node into the spanning tree in dynamic network simplex algorithm ......................... 182

Figure 8.9  The new spanning tree after inserting nodes 9 and 10 (see Figure 8.1). ................................................................. 183

Figure 8.10  Block diagram of the software and algorithm (DNSA+) in the dynamic aspect ....................................................... 184

Figure 8.11  A comparison of the number of iterations in DNSA+ and NSA+. ........................................................................... 186

Figure 9.1  An example of the incomplete case of the MCF-AGV model with two AGVs and four jobs. ........................................... 190

Figure 9.2  The block diagram of Greedy Vehicle Search. ................................................................................................................ 193

Figure 9.3  The pseudo-code of Greedy Vehicle Search in dynamic aspect .................................................................................. 194

Figure 9.4  The block diagram of the software and algorithm (GVS) in dynamic aspect ............................................................... 194

Figure 9.5  A comparison of NSA± and GVS for traveling and waiting times of the vehicles. ............................................................ 195

Figure 9.6  The number of carried jobs by NSA± and GVS during six-hour simulation ................................................................. 196

Figure 9.7  A comparison of NSA± and GVS for the average lateness from the appointment time ....................................................... 197

Figure 9.8  CPU-Time required solving the static problems by GVS ......................................................................................... 198

Figure 9.9  CPU-Time required solving the dynamic problems by GVS ..................................................................................... 200

Figure 10.1  Layout of a seaport container terminal. See [53]. ....................................................................................................... 204
Figure 10.2  A pseudo-code for SAM. See [46]. .......................................................... 208

Figure 11.1  Layout of the automated container terminal. (Adopted from [94].) .......................................................... 214

Figure 11.2  Loading and unloading process. (Adopted from [94].) .................. 215

Figure 11.3  An example of the model for 2 AGVs and 4 container jobs. ....... 224

Figure 11.4  The source and destination of sixteen containers. ....................... 227

Figure 11.5  Flowchart of the presented sorting genetic algorithm .................. 228

Figure 11.6  A docked ship with five QCs worked on. .................................. 228

Figure 11.7  A three-level chromosome for sixteen container jobs with ten inbound jobs and six outbound jobs. ............................ 229

Figure 11.8  Selected parents with intersection points 6 and 10. ................. 230

Figure 11.9  Genes exchanging between intersection points ........................ 230

Figure 11.10 Adding non-repetitive containers to children. .......................... 230

Figure 11.11 Adding non-repetitive containers to children .......................... 231

Figure 11.12 Swap mutation operation. ....................................................... 231

Figure 11.13 Main effects plot for means. .................................................... 233

Figure 11.14 Main effects plot for SN ratios .................................................. 233

Figure 11.15 Convergence of GA with 100 generations for solving the problems .......................................................... 234

Figure 11.16 A comparison of log(CPU-Time spent by GA, PSO, GA+PSO, and PSO+GA algorithms) .................................................... 235

Figure 11.17 A comparison of objective function values for GA, PSO, GA+PSO, and PSO+GA algorithms ............................ 235

Figure 11.18 The waiting times of AGVs and cranes. .................................. 236

Figure Appendix.1 CPU-Time required solving the graph model................ 251

Figure Appendix.2 The main form of the software ....................................... 253

Figure Appendix.3 An output of running the software in static aspect .......... 255

Figure Appendix.4 An output of running the software in dynamic aspect, showing the information of quay cranes, container jobs and vehicles ................ 255
List of Tables

Table 1.1 Business Container Terminals in the World (in Million TEU): The Top 20 Container Ports...

Table 1.2 The Drewry Container Port Throughput Indices in Two Years, 2020 and 2021...

Table 2.1 The Strengths and Weaknesses of the Major Classifications over the Decisions in Container Terminals...

Table 3.1 The Major Research Done Around Allocation of Berths to Arriving Vessels and Quay Cranes to Docked Vessels...

Table 3.2 The Major Research Done Around the Storage Space Assignment in Container Terminals...

Table 3.3 The Major Research Done Around the RTGC Deployment in Container Terminals...

Table 3.4 The Major Research Done Around the Scheduling and Routing Vehicles in Ports...

Table 3.5 The Major Research Dedicated to the Decision of Appointment Times for External Trucks...

Table 3.6 Container Terminals Around the World and Their Decisions...

Table 4.1 Major Solutions in the Frameworks with Considerations for Choosing...

Table 4.2 Summary of Vehicle Routing Problems and Solutions, before 2000. See [156].

Table 4.3 Summary of Algorithms for AGVs in General Path Topologies, before 2000. See [153].

Table 4.4 Summary of Algorithms for AGVs in Specific Path Topologies, before 2000. See [153].
Table 4.5  Summary of Static and Dynamic Routing Algorithms for
 AGVs in General Path Topology, before 2000. See [153]. ............... 90
Table 4.6  Summary of Algorithms for Static Scheduling of AGVs,
 since 2000 ..........................................................................................94
Table 4.7  Summary of Dynamic Routing Algorithms for AGVs,
 since 2000 ..........................................................................................96
Table 4.8  General Framework for Implementation of the Five
 Scheduling Decisions in Container Terminals.............................. 103
Table 4.9  Some Important Indices to Evaluate the Decisions in the
 Container Terminals...........................................................................106
Table 5.1  Example of Traveling Time (Seconds) between Two
 Different Points in the Port.............................................................. 112
Table 5.2  Appointment Time of Containers Jobs .......................... 113
Table 6.1  Experimental Results of Network Simplex Algorithm in
 Static Fashion ..................................................................................145
Table 6.2  Regression Result for CPU-Time Required Solving the
 Problem by NSA (Based on the Number of Jobs) ..........................149
Table 6.3  Regression Result for CPU-Time Required Solving the
 Problem by NSA (Based on the Number of Arcs) ..........................149
Table 6.4  Regression Result for CPU-Time Required Solving the
 Problem by NSA (Based on the Number of Jobs) ..........................149
Table 6.5  Experimental Results for a Comparison between NSA and
 NSA+ .................................................................................................157
Table 6.6  The Result of $t$-Test for the Two Algorithms, NSA and
 NSA+ .................................................................................................159
Table 7.1  Memory Allocation for the Arcs of the MCF-AGV Model and
 Its Algorithm ....................................................................................176
Table 7.2  The Result of $t$-Test for the Two Algorithms, DNSA+ and
 NSA+ .................................................................................................186
Table 7.3  A Comparison between NSA and Its Extensions ..............188
Table 8.1  The Result of $t$-Test for the Two Algorithms, GVS
 and NSA+ ..........................................................................................197
Table 8.2  Regression Result for CPU-Time Required to Finding a Local
 Optimum by GVS for Static Problem..............................................199
Table 10.1  Simulated Annealing Parameters .....................................209
Table 10.2  A Comparison between Different Options for the Initial Points of SAM ................................................................. 210
Table 10.3  The Result of $t$-Test from SAM with Different Options for Initial Solution........................................................................ 211
Table 11.1  Summary of the Review Around Integrated Handling Equipment Scheduling. See [106]. ........................................ 219
Table 11.2  Known Parameters before Decision Making.......................... 224
Table 11.3  Decision Variables.................................................................. 226
Table 11.4  The Factors Names and Values................................................. 232
Table 11.5  Parameters and Values Used in the Genetic Algorithm.............. 234
Table 11.6  The Experimental Results of Solving Sixteen Problems.............. 237
Table 12.1  A Summary of the Algorithms Studied in This Book for AGV Scheduling................................................................. 243
# List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Term / Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGV</td>
<td>Automated Guided Vehicle</td>
</tr>
<tr>
<td>ALV</td>
<td>Automated Lifting Vehicles</td>
</tr>
<tr>
<td>BDE</td>
<td>Borland Database Engine</td>
</tr>
<tr>
<td>CSOPs</td>
<td>Constraint Satisfaction Optimization Problems</td>
</tr>
<tr>
<td>DNSA</td>
<td>Dynamic Network Simplex Algorithm</td>
</tr>
<tr>
<td>DNSA+</td>
<td>Dynamic Network Simplex Plus Algorithm</td>
</tr>
<tr>
<td>DSSAGV</td>
<td>Dynamic Scheduling Software for Automated Guided Vehicles</td>
</tr>
<tr>
<td>ERD</td>
<td>Entity Relationship Diagram</td>
</tr>
<tr>
<td>GVS</td>
<td>Greedy Vehicle Search</td>
</tr>
<tr>
<td>HOTFRAME</td>
<td>Heuristic OpTimization FRAMEwork</td>
</tr>
<tr>
<td>IT</td>
<td>Internal Trucks</td>
</tr>
<tr>
<td>MCF</td>
<td>Minimum Cost Flow</td>
</tr>
<tr>
<td>MCF-AGV</td>
<td>Minimum Cost Flow model for Scheduling problem of AGVs</td>
</tr>
<tr>
<td>NSA</td>
<td>Network Simplex Algorithm</td>
</tr>
<tr>
<td>NSA+</td>
<td>Network Simplex Plus Algorithm</td>
</tr>
<tr>
<td>OSA</td>
<td>Original Simplex Algorithm</td>
</tr>
<tr>
<td>PSCDS</td>
<td>Primary Storage Containers Discharge</td>
</tr>
<tr>
<td>PSCPI</td>
<td>Primary Storage Containers Pickup</td>
</tr>
<tr>
<td>PSCSS</td>
<td>Primary Storage Containers to Secondary Storage</td>
</tr>
<tr>
<td>QC</td>
<td>Quay Cranes</td>
</tr>
<tr>
<td>RTGC</td>
<td>Rubber Tyred Gantry Cranes</td>
</tr>
<tr>
<td>SAM</td>
<td>Simulated Annealing Method</td>
</tr>
<tr>
<td>SC</td>
<td>Straddle Carrier</td>
</tr>
<tr>
<td>SDSAGV</td>
<td>Static and Dynamic Scheduling of Automated Guided Vehicles</td>
</tr>
<tr>
<td>SSCGD</td>
<td>Secondary Storage Containers Grounding</td>
</tr>
<tr>
<td>SSCPI</td>
<td>Secondary Storage Containers for Pickup</td>
</tr>
<tr>
<td>SSCPS</td>
<td>Secondary Storage Containers to Primary Storage</td>
</tr>
<tr>
<td>TG</td>
<td>Terminal Gate</td>
</tr>
<tr>
<td>TSS</td>
<td>Taxi Service System</td>
</tr>
<tr>
<td>VRP</td>
<td>Vehicle Routing Problem</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>VRPTW</td>
<td>Vehicle Routing Problem with Time Window</td>
</tr>
<tr>
<td>XT</td>
<td>eXternal Truck</td>
</tr>
<tr>
<td>YC</td>
<td>Yard Cranes</td>
</tr>
</tbody>
</table>
Preface

This book is a scientific report of a very solid piece of research. It is useful for port authorities and researchers, including specialists and graduate students in operation research. The aim of publishing this book is to publicize our work, which advances state-of-the-art algorithms in network flow problems. For students, it provides the most comprehensive survey of the field. It also provides a rigorous formulation of the problems in port automation. For specialists, it provides novel and efficient algorithms for network flow problems.

This book is divided into two major parts: the optimization problems faced by today’s modern container terminals, in general, and the advanced algorithms to tackle the scheduling of automated guided vehicles, in particular. Although we focused on the vehicle scheduling problem in ports, the techniques that we developed are very general.

We created literature over problems in container terminal. The problems are classified into five scheduling decisions. For each of the decisions an overview of the literature is presented. After that, each of the decisions is formulated as Constraint Satisfaction and Optimization Problems (CSOPs). The literature also includes solutions, implementations, and performance. The solutions are classified and summarized.

We then extend the Network Simplex Algorithm (NSA), the fastest algorithm to solve the Minimum Cost Flow problem, and found out four advanced algorithms. In order to verify and validate the algorithms, we chose one of the challenging problems in ports, the scheduling problem of Automated Guided Vehicles (AGVs) in container terminals.

Recent trends toward larger and more complex ports necessitate the use of heterogeneous AGVs. In this book, we worked on this kind of AGVs. If the capacity of the AGVs increases, the problem is an NP-hard problem. This problem has a huge search space and was tackled by the Simulated Annealing Method (SAM). Three approaches for its initial solution and a neighborhood function to the search method were implemented. A hybrid of SAM and NSA also was used. This hybrid was applied to the heterogeneous AGVs scheduling problem in container terminals. Several of the same random problems were generated, solved by SAM with the proposed approaches and the simulation results were compared. The experimental
results showed that NSA provides a good initial solution for SAM when the capacity of AGVs is heterogeneous.

In recent years, integrated management of equipment in automated container terminals has become more necessary and has attracted more attention. To do this, we studied this problem with the aim of reducing the service time of berthed ships. The complexity of the proposed problem was investigated and then the problem was formulated as a linear integer-programming model. A solution based on a combination of the greedy algorithm and the genetic algorithm was proposed. This solution was named Sorting Genetic Algorithm (SGA).

This book develops a complete package for the scheduling problems of AGVs in ports. The problem divulges two types: static and dynamic. In static problems, where there is no change in situation, the challenge is to find out more efficient and faster algorithms to tackle the large-scale problems. In dynamic problems, the challenge is to respond to the changes while solving the new problem faster. The algorithms developed in this book are also two types, complete and incomplete. The complete algorithms find out the global solution for the problem, whereas the incomplete algorithms find out a local optimum solution. The experiments were performed to evaluate the performance of the developed algorithms on a large number of generated instances of the problem and the results presented were of high quality.

Hassan Rashidi
Professor in Computer Science,
Department of Statistics, Mathematics and Computer Science,
Allameh Tabataba’i University,
Tehran,
Iran

Edward P. K. Tsang
Professor in Computer Science,
School of Computer Science and Electronic Engineering, University of Essex,
Colchester,
U.K.
Acknowledgments

Many people have helped us in various ways in the preparation of this book. First of all, we are grateful to Dr. John Ford, from the School of Computer Science and Electronic Engineering at the University of Essex, for his suggestion that we should develop the Dynamic Network Simplex Algorithm and his comments on this research. We would like to thank Prof. Hu, the head of Robotics Research Group at the University of Essex, who proposed a few suggestions on our software.

We would like to thank the School of Computer Science and Electronic Engineering for the harmonious environment and the Computing Service at the University of Essex for the excellent computer facilities to perform the computational experiments reported here. We also thank the School for providing a few chances to graduate students as the students saw results of their research presented, and got the academic staff’s views.

We also wish to thank Professor Sanja Petrovic, from the School of Computer Science and IT at the University of Nottingham, for giving us some valuable comments. We would like to thank Professor Klaus McDonald-Maier, from the School of Computer Science and Electronic Engineering at the University of Essex, for his feedback.

We thank Demi Stevens, from the Copywriting Company in the UK, for many helpful remarks and for proof-reading of the first edition of this book.

Above all, our greatest thanks go to our families for their patience, encouragement, and support while we were working on this book.
Authors

Hassan Rashidi earned a BSc in computer engineering in 1986 and an MSc in systems engineering and planning in 1989 with the highest honors at the Isfahan University of Technology, Isfahan, Iran. He joined the Department of Computer Science, University of Essex, United Kingdom, as a PhD student in 2002 and earned his PhD in 2006. He was a researcher in British Telecom research center in United Kingdom in 2005. He is currently a professor of computer science at Allameh Tabataba’i University, Tehran, Iran, and a visiting academic at the University of Essex. He is an international expert in the applications of the network simplex algorithm to automated vehicle scheduling and has published many conference and journal papers.

Edward P. K. Tsang has a first degree in business administration (major in finance) and an MSc and a PhD in computer science. He has broad interests in applied artificial intelligence, particularly constraint satisfaction, computational finance, heuristic search, and scheduling. He is currently a professor at the School of Computer Science and Electronic Engineering at the University of Essex, where he leads the computational finance group and the constraint satisfaction and optimization group. He is also the director of the Centre for Computational Finance and Economic Agents, an interdisciplinary center. He founded the Technical Committee for Computational Finance and Economics under the IEEE Computational Intelligence Society.
Chapter 1

Introduction

There are more than two thousand ports over the world. These ports play an important role in global manufacturing and international business, as ships come to load and/or unload their cargos. The cargo ships can be classified into two types. The first type transports huge quantities of commodities like crude oil, coal, grain, etc. The second type usually carries goods that are packed into steel containers of standard sizes. Part One of this book concentrates on the second type, which attracted more attention in both investment and automation during the last decade.

In the past few decades, much research has been devoted to the technology of Automated Guided Vehicle (AGV) systems, both in hardware and software [153]. Nowadays they have become popular over the world for automatic material handling and flexible manufacturing systems. Increasingly, these unmanned vehicles are also becoming the common mode of container transport in the seaport. Part Two of this book is therefore dedicated to the advanced algorithms tackling the scheduling problem of AGVs. Although we focused on the transport scheduling inside the port, the techniques that we developed are very general.

1.1 Objectives

There are two main objectives in this book. The first objective is to study optimization problems in container terminals. The second objective is dedicated to developing advanced algorithms for the scheduling problem of AGVs in ports.
1.1.1 Optimization in Ports

The first objective of publishing this book is a response to the growth of containerization and globalization. Since the 1960s, due to both increasing containerization and increasing world trade, new container terminals are being built and existing ones extended. Today over 60% of the world’s deep-sea general cargo is transported in containers, whereas some routes, especially between economically strong and stable countries, are containerized up to 100% [175]. Table 1.1 presents the twenty busiest container ports in the world in terms of TEUs (Twenty-foot Equivalent Unit) handled. We note that the total volume handled in 2020 increased by 11.8% compared to 2016 and the major growth was in Ningbo-Zhoushan (China), increased by 32.96% compared to 2016. Container terminals are continuously challenged to adjust their throughput capacity to match demand. Consequently, many opportunities arise for new approaches in container terminal design, material handling equipment, and operations research applications.

Drewry is an independent maritime research consultancy offering market insights and advisory services to senior stakeholders across global shipping. The result of a study on Container Port Throughput is presented in Table 1.1. The Drewry Container Port Throughput Indices are a series of volume growth/decline indices based on monthly throughput data for a sample of over 235 ports worldwide, representing over 75% of global volumes. The base point for the indices is January 2012 = 100.

The main observations obtained from this table are as follows:

- **Observation 1-1:** The Drewry Port Throughput Index rose to 141.3 points in May 2021, an increase of 3.3 points over April, which was very nearly enough to restore it to March’s reading. Annual growth of 15.8% for the month confirms that the worldwide volume recovery is showing no signs of slowing down. Container throughput is expected to increase further through the 3Q21 peak season, after which we anticipate a modest seasonal slowdown in the final quarter. Growth forecasts remain highly sensitive to COVID-19 developments.

- **Observation 1-2:** Greater China ports index recorded a 9.8% year-on-year increase in May with growth mostly concentrated at the largest Chinese gateways. The top six ports (Shanghai, Ningbo, Shenzhen, Qingdao, Tianjin, and Xiamen) accounted for close to 90% of the volume growth, representing more than 65% of the total throughput of the region. We expect China’s throughput growth in full-year 2021 to be the highest in 10 years.

- **Observation 1-3:** The May throughput index for Asia (ex-China) increased by only 1.4% month-on-month to 134.6 points, but the annual comparison returned an impressive increase of 15.8% with the top three regional hubs (Singapore, Port Kelang, and Busan) witnessing double-digit annual growth. In percentage terms, Port Kelang recorded the highest growth of 33%, while in absolute terms, Singapore topped the list by handling 3.2 M-TEU, an increase of 410,183 TEU over April 2021.
Table 1.1 Business Container Terminals in the World (in Million TEU): The Top 20 Container Ports

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Shanghai, China</td>
<td>37.13</td>
<td>40.23</td>
<td>42.01</td>
<td>43.30</td>
<td>43.5</td>
<td>17.16</td>
</tr>
<tr>
<td>2</td>
<td>Singapore</td>
<td>30.9</td>
<td>33.67</td>
<td>36.6</td>
<td>37.20</td>
<td>36.6</td>
<td>18.45</td>
</tr>
<tr>
<td>3</td>
<td>Ningbo-Zhoushan, China</td>
<td>21.6</td>
<td>24.61</td>
<td>26.35</td>
<td>27.49</td>
<td>28.72</td>
<td>32.96</td>
</tr>
<tr>
<td>4</td>
<td>Shenzhen, China</td>
<td>23.97</td>
<td>25.21</td>
<td>27.74</td>
<td>25.77</td>
<td>26.55</td>
<td>10.76</td>
</tr>
<tr>
<td>5</td>
<td>Guangzhou Harbor, China</td>
<td>18.85</td>
<td>20.37</td>
<td>21.87</td>
<td>23.23</td>
<td>23.19</td>
<td>23.02</td>
</tr>
<tr>
<td>7</td>
<td>Qingdao, China</td>
<td>18.01</td>
<td>18.3</td>
<td>18.26</td>
<td>21.01</td>
<td>22.00</td>
<td>22.15</td>
</tr>
<tr>
<td>8</td>
<td>Hong Kong, SAR, China</td>
<td>19.81</td>
<td>20.76</td>
<td>19.6</td>
<td>18.30</td>
<td>20.07</td>
<td>1.31</td>
</tr>
<tr>
<td>9</td>
<td>Tianjin, China</td>
<td>14.49</td>
<td>15.07</td>
<td>16</td>
<td>17.30</td>
<td>18.35</td>
<td>26.64</td>
</tr>
<tr>
<td>10</td>
<td>Rotterdam, The Netherlands</td>
<td>12.38</td>
<td>13.73</td>
<td>14.51</td>
<td>14.82</td>
<td>14.35</td>
<td>15.91</td>
</tr>
<tr>
<td>11</td>
<td>Jebel Ali, Dubai, United Arab Emirates</td>
<td>15.73</td>
<td>15.37</td>
<td>14.95</td>
<td>14.11</td>
<td>13.5</td>
<td>−14.18</td>
</tr>
<tr>
<td>12</td>
<td>Port Klang, Malaysia</td>
<td>13.2</td>
<td>13.73</td>
<td>12.32</td>
<td>13.58</td>
<td>13.24</td>
<td>0.30</td>
</tr>
<tr>
<td>13</td>
<td>Xiamen, China</td>
<td>9.61</td>
<td>10.38</td>
<td>10</td>
<td>11.12</td>
<td>11.41</td>
<td>18.73</td>
</tr>
<tr>
<td>14</td>
<td>Antwerp, Belgium</td>
<td>10.04</td>
<td>10.45</td>
<td>11.1</td>
<td>11.10</td>
<td>12.04</td>
<td>19.92</td>
</tr>
<tr>
<td>15</td>
<td>Kaohsiung, Taiwan, China</td>
<td>10.46</td>
<td>10.27</td>
<td>10.45</td>
<td>10.42</td>
<td>9.62</td>
<td>−8.03</td>
</tr>
</tbody>
</table>

(Continued)
Table 1.1 Business Container Terminals in the World (in Million TEU): The Top 20 Container Ports (Continued)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>Dalian, China</td>
<td>9.61</td>
<td>9.7</td>
<td>9.77</td>
<td>10.21</td>
<td>6.54</td>
<td>−31.95</td>
</tr>
<tr>
<td>17</td>
<td>Los Angeles, USA</td>
<td>8.86</td>
<td>9.43</td>
<td>9.46</td>
<td>9.30</td>
<td>9.2</td>
<td>3.84</td>
</tr>
<tr>
<td>18</td>
<td>Hamburg, Germany</td>
<td>8.91</td>
<td>8.86</td>
<td>8.73</td>
<td>9.30</td>
<td>8.7</td>
<td>−2.36</td>
</tr>
<tr>
<td>19</td>
<td>Tanjung Pelepas, Malaysia</td>
<td>8.28</td>
<td>8.38</td>
<td>8.96</td>
<td>9.10</td>
<td>9.85</td>
<td>18.96</td>
</tr>
<tr>
<td>20</td>
<td>Laem Chabang, Thailand</td>
<td>7.22</td>
<td>7.78</td>
<td>8.07</td>
<td>8.10</td>
<td>7.55</td>
<td>4.57</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>318.91</td>
<td>336.79</td>
<td>348.41</td>
<td>356.75</td>
<td>356.57</td>
<td>11.81</td>
</tr>
</tbody>
</table>

Source: [https://www.worldshipping.org/top-50-ports](https://www.worldshipping.org/top-50-ports)

Table 1.2 The Drewry Container Port Throughput Indices in Two Years, 2020 and 2021

<table>
<thead>
<tr>
<th>Index</th>
<th>May 2020</th>
<th>April 2021</th>
<th>May 2021</th>
<th>Monthly Change (%)</th>
<th>Annual Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>122.5</td>
<td>138.0</td>
<td>141.3</td>
<td>2.4%</td>
<td>15.4%</td>
</tr>
<tr>
<td>China</td>
<td>137.7</td>
<td>147.1</td>
<td>151.2</td>
<td>2.8%</td>
<td>9.8%</td>
</tr>
<tr>
<td>Asia exc. China</td>
<td>116.3</td>
<td>133.2</td>
<td>134.6</td>
<td>1.0%</td>
<td>15.7%</td>
</tr>
<tr>
<td>Middle East &amp; South Asia</td>
<td>112.8</td>
<td>132.7</td>
<td>131.8</td>
<td>−0.7%</td>
<td>16.9%</td>
</tr>
<tr>
<td>Europe</td>
<td>109.5</td>
<td>122.2</td>
<td>122.3</td>
<td>0.1%</td>
<td>11.7%</td>
</tr>
<tr>
<td>North America</td>
<td>122.0</td>
<td>157.0</td>
<td>171.0</td>
<td>9.0%</td>
<td>40.3%</td>
</tr>
<tr>
<td>Latin America</td>
<td>109.2</td>
<td>122.8</td>
<td>128.6</td>
<td>4.7%</td>
<td>17.8%</td>
</tr>
<tr>
<td>Africa*</td>
<td>82.9</td>
<td>112.8</td>
<td>107.3</td>
<td>−4.9%</td>
<td>29.4%</td>
</tr>
<tr>
<td>Oceania</td>
<td>120.8</td>
<td>134.9</td>
<td>141.1</td>
<td>4.6%</td>
<td>16.8%</td>
</tr>
</tbody>
</table>

Source: [https://www.hellenicshippingnews.com/drewry-container-port-throughput-rises-during-may/](https://www.hellenicshippingnews.com/drewry-container-port-throughput-rises-during-may/)