

# Contents

Preface	v
<b>1 Scheduling Models</b>	<b>1</b>
1.1 The RCPSP and some Generalizations . . . . .	1
1.1.1 The RCPSP . . . . .	1
1.1.2 Applications of the RCPSP . . . . .	12
1.2 Machine Scheduling . . . . .	17
1.2.1 Single-machine scheduling . . . . .	18
1.2.2 Parallel machine scheduling . . . . .	18
1.2.3 Shop scheduling . . . . .	19
1.2.4 Multi-processor task scheduling . . . . .	21
1.3 Reference Notes . . . . .	22
<b>2 Algorithms and Complexity</b>	<b>23</b>
2.1 Easy and Hard Problems . . . . .	23
2.1.1 Polynomially solvable problems . . . . .	24
2.1.2 NP-hard problems . . . . .	24
2.2 Shortest Path Algorithms . . . . .	29
2.2.1 Dijkstra's algorithm . . . . .	29
2.2.2 Label-correcting algorithms . . . . .	33
2.2.3 Detection of negative cycles . . . . .	36
2.2.4 Floyd-Warshall algorithm . . . . .	36
2.3 Linear and Integer Programming . . . . .	38
2.3.1 Linear programs and the simplex algorithm . . . . .	38
2.3.2 Duality . . . . .	45
2.3.3 The revised simplex method . . . . .	49
2.3.4 Linear programs with integer variables . . . . .	51

2.3.5	Delayed column generation techniques . . . . .	53
2.4	Network Flow Algorithms . . . . .	56
2.4.1	The minimum cost flow problem . . . . .	56
2.4.2	The residual network and decomposition of flows . . . . .	58
2.4.3	The maximum flow problem . . . . .	62
2.4.4	Flows and cuts . . . . .	65
2.4.5	Algorithms for the maximum flow problem . . . . .	67
2.4.6	Algorithms for the minimum cost flow problem . . . . .	72
2.5	Branch-and-Bound Algorithms . . . . .	74
2.5.1	Basic concepts . . . . .	74
2.5.2	The knapsack problem . . . . .	75
2.6	Dynamic Programming . . . . .	80
2.7	Local Search and Genetic Algorithms . . . . .	82
2.7.1	Local search algorithms . . . . .	82
2.7.2	Genetic algorithms . . . . .	88
2.8	Reference Notes . . . . .	90
<b>3</b>	<b>Resource-Constrained Project Scheduling</b>	<b>91</b>
3.1	Basics . . . . .	91
3.2	Constraint Propagation . . . . .	93
3.2.1	Basic relations . . . . .	93
3.2.2	Start-start distance matrix . . . . .	94
3.2.3	Symmetric triples and extensions . . . . .	96
3.2.4	Disjunctive sets . . . . .	99
3.2.5	Cumulative resources . . . . .	114
3.2.6	Constraint propagation for the multi-mode case . . . . .	114
3.2.7	Reference notes . . . . .	120
3.3	Lower Bounds . . . . .	121
3.3.1	Combinatorial constructive lower bounds . . . . .	122
3.3.2	An LP-based constructive lower bound . . . . .	124
3.3.3	An LP-based destructive method . . . . .	128
3.3.4	A destructive method for the multi-mode case . . . . .	136
3.3.5	Reference notes . . . . .	141
3.4	Heuristic Methods . . . . .	142

3.4.1	A classification of schedules . . . . .	142
3.4.2	Schedule generation schemes . . . . .	144
3.4.3	Priority-based heuristics . . . . .	150
3.4.4	Local search algorithms . . . . .	151
3.4.5	Genetic algorithms . . . . .	153
3.4.6	Heuristics for the multi-mode case . . . . .	156
3.4.7	Reference notes . . . . .	156
3.5	Branch-and-Bound Algorithms . . . . .	157
3.5.1	An algorithm based on precedence trees . . . . .	157
3.5.2	An algorithm based on extension alternatives . . . . .	161
3.5.3	An algorithm based on delaying alternatives . . . . .	165
3.5.4	An algorithm based on schedule schemes . . . . .	171
3.5.5	Algorithms for the multi-mode case . . . . .	175
3.5.6	Reference notes . . . . .	177
3.6	General Objective Functions . . . . .	178
3.6.1	Regular functions . . . . .	179
3.6.2	Linear functions . . . . .	179
3.6.3	Convex piecewise linear functions . . . . .	181
3.6.4	General sum functions . . . . .	183
3.6.5	Reference notes . . . . .	188
<b>4</b>	<b>Complex Job-Shop Scheduling</b>	<b>189</b>
4.1	The Job-Shop Problem . . . . .	189
4.1.1	Problem formulation . . . . .	189
4.1.2	The disjunctive graph model . . . . .	190
4.2	Heuristic Methods . . . . .	194
4.3	Branch-and-Bound Algorithms . . . . .	202
4.4	Generalizations . . . . .	203
4.5	Job-Shop Problems with Flexible Machines . . . . .	209
4.5.1	Problem formulation . . . . .	209
4.5.2	Heuristic methods . . . . .	210
4.6	Job-Shop Problems with Transport Robots . . . . .	217
4.6.1	Problem formulation . . . . .	217
4.6.2	Problems without transportation conflicts . . . . .	218

4.6.3	Problems with transportation conflicts . . . . .	221
4.6.4	Constraint propagation . . . . .	229
4.6.5	Lower bounds . . . . .	235
4.6.6	Heuristic methods . . . . .	246
4.7	Job-Shop Problems with Limited Buffers . . . . .	250
4.7.1	Problem formulation . . . . .	250
4.7.2	Representation of solutions . . . . .	251
4.7.3	Flow-shop problems with intermediate buffers . . . . .	256
4.7.4	Job-shop problems with pairwise buffers . . . . .	258
4.7.5	Job-shop problems with output buffers . . . . .	258
4.7.6	Job-shop problems with input buffers . . . . .	264
4.7.7	Job-shop problems with job-dependent buffers . . . . .	265
4.8	Reference Notes . . . . .	266
	<b>Bibliography</b>	<b>269</b>
	<b>Index</b>	<b>281</b>