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Ant Colony Optimisation for Power Plant Maintenance Scheduling

by
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To my loving parents,
Kim Lam Wong and Kon Choong Foong:

For what I have been taught and untaught.

Abstract

Maintenance of power plants is aimed at extending the life and reducing the risk of sudden breakdown of power generating units. Traditionally, power generating units have been scheduled for maintenance in periods to ensure that the demand of the system is fully met and the reliability of the system is maximized. However, in a deregulated power industry, the pressure of maintaining generating units is also driven by the potential revenue received by participating in the electricity market. Ideally, hydropower generating units are required to operate during periods when electricity prices are high and to be able to be taken offline for maintenance when the price is low. Therefore, determination of the optimum time periods for maintenance of generating units in a power system has become an important task from both a system reliability and an economic point of view. Due to the extremely large number of potential maintenance schedules, a systematic approach is required to ensure that optimal or near-optimal maintenance schedules are obtained within an acceptable timeframe.

Metaheustics are high-level algorithmic frameworks that aim to solve combinatorial optimisation problems with a large search space in a reasonable computational run time. Inspired by the foraging behavior of ant colonies, Ant Colony Optimisation (ACO) is a relatively new metaheuristic for combinatorial optimisation. The application of ACO to a number of different applications has provided encouraging results when applied to scheduling, including the job-shop, flow-shop, machine tardiness and resource-constrained project scheduling problems.

In this thesis, a formulation is developed that enables ACO to be applied to the generalized power plant maintenance scheduling optimisation (PPMSO) problem. The formulation caters for all constraints generally encountered as part of real-world PPMSO problems, including system demands and reliability levels, precedence rules between maintenance tasks, public holidays and minimum outage durations in the case of shortening of maintenance tasks. As part of the formulation, a new heuristic and a new local search strategy have been developed. The new ACO-PPMSO formulation has been tested extensively on two benchmark PPMSO problems from the literature, including a 21-unit and a 22-unit problem. It was found that the ACO-PPMSO formulation resulted in significant improvements in performance for both case studies compared with the results obtained in previous studies. In addition, the new heuristic formulation was found to be useful in finding maintenance schedules that result in more evenly spread reserve capacity and resource allocations. When tested using a modified version of the 21-unit and the 22-unit problems, the new local search strategy specifically designed for duration shortening was found to be effective in searching locally for maintenance schedules that require minimal shortening of outage duration. The ACO-PPMSO formulation was also successfully able to cater for all constraints as specified in both original and the modified versions of the two benchmark case studies.

In order to further test the ACO-PPMSO formulation developed, it was first applied to a scaled-down version of the Hydro Tasmania hydropower system (five power stations) and then to the full system (55 generating units). As part of the studies, the ACO-PPMSO formulation was linked with the simulation model used by Hydro Tasmania to assess the impact of various maintenance schedules on the total energy in storage of the system at the end of the planning horizon, the total thermal generation, the total number of days where the reliability level is not met, as well as the total unserved energy throughout the planning horizon. A number of constraints were considered, including the anticipated system demands, a 30% capacity reliability level, the minimum and maximum durations between related maintenance tasks, the precedence constraints and the minimum outage duration of each task in the case of shortening of maintenance tasks. The maintenance schedule was optimised for the maximum end-of-horizon total energy in storage, the minimum thermal generation and the minimum total outage durations shortened and deferred, under 77 different inflow conditions. The optimal maintenance schedule obtained compared favourably with that obtained by Hydro Tasmania over many years based on experience. Specifically, the ACO-PPMSO schedule results in higher end-of-horizon total energy in storage and satisfies both hard and soft constraints, which overall equates to over $0.5 million dollars of savings when compared to the schedule obtained using the practitioners' experience and engineering judgment. The ACO-PPMSO algorithm was also shown to be a useful decision-making tool for scheduling maintenance under different circumstances when tested with four scenarios commonly encountered in practical maintenance scheduling problems.

In conclusion, the ACO-PPMSO formulation developed, tested and applied as part of this thesis research provides a powerful and flexible means of obtaining optimal or near-optimal maintenance schedules for power plants.

Declaration

I, **Wai Kuan Foong**, declare that the work presented in this thesis is, to the best of my knowledge and belief, original and my own work, except as acknowledged in the text, and that the material has not been submitted, either in whole or in part, for a degree at this or any other university.

I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

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Table of Contents

Abstract **i**
Declaration **iii**
Acknowledgements **iv**
Table of Contents **v**
List of Appendices **vii**
List of Figures **viii**
List of Tables **xiii**
Glossary of Selected Acronyms and Notation **xv**

CHAPTER 1 INTRODUCTION 1

1.1 Research background 1
1.2 Research objectives 2
1.3 Thesis layout 3

CHAPTER 2 LITERATURE REVIEW 5

2.1 Power plant maintenance scheduling optimisation 5
  2.1.1 Objectives 6
  2.1.2 Constraints 11
  2.1.3 Deregulation of electricity market 13
2.2 Optimisation methods previously adopted for PPMSO 14
  2.2.1 Design requirements for a maintenance scheduling tool 14
  2.2.2 Heuristic approaches 16
  2.2.3 Mathematical programming 17
  2.2.4 Expert systems 20
  2.2.5 Metaheuristics 20
  2.2.6 Comparison of optimisation methods for PPMSO 36
2.3 Summary and conclusions 39

CHAPTER 3 ANT COLONY OPTIMISATION METAHEURISTIC 40

3.1 From Real Ants to Artificial Ants 40
  3.1.1 Foraging behavior of real ants 40
  3.1.2 Artificial ants 45
3.2 ACO for Combinatorial Problems 46
  3.2.1 Problem representation 46
  3.2.2 The ACO metaheuristic: a general framework 47
  3.2.3 Prerequisites of ACO implementation 49

3.3 Variants of Ant Colony Optimisation algorithms 51
3.3.1 Ant System (AS) and its direct successors 52
3.3.2 Non-AS-based ACO algorithms 57
3.4 Ant Colony Optimisation Applications 60
3.4.1 Benchmark scheduling optimisation problems 60
3.4.2 Real-world optimisation problems 64
3.5 Motivation for Applying ACO to PPMSO 68

CHAPTER 4 PROPOSED APPROACH TO MAINTENANCE SCHEDULING OPTIMISATION 70

4.1 Definition of power plant maintenance scheduling optimisation (PPMSO) 70
4.2 Proposed ACO formulation for PPMSO 75
4.3 The ACO-PPMSO algorithm 77
4.3.1 Initialization 77
4.3.2 Construction of a trial maintenance schedule 78
4.3.3 Evaluation of trial maintenance schedule 82
4.3.4 Local search 83
4.3.5 Pheromone updating 85
4.3.6 Termination of run 87
4.4 Constraint handling techniques in ACO-PPMSO.................................. 88
4.5 Software development 94
4.6 Summary 95

CHAPTER 5 TESTING ON BENCHMARK CASE STUDIES 97

5.1 Benchmark case studies 98
5.1.1 21-unit system 98
5.1.2 22-unit system 103
5.2 Modified case studies 107
5.2.1 Modified 21-unit case study 108
5.2.2 Modified 22-unit case study 112
5.3 Experimental Procedure 115
5.4 Results and analysis... 116
5.5 Summary and conclusions 163

CHAPTER 6 HYDROELECTRIC POWER CASE STUDIES 165

6.1 Background 165

6.2 Five-Station Hydropower System 166
6.2.1 Problem specification 167
6.2.2 Problem formulation 170
6.2.3 Analysis conducted 172
6.2.4 Results and discussion 177
6.2.5 Summary 199
6.3 Full Hydro Tasmania Maintenance Scheduling Case Study 200
6.3.1 Problem specification 200
6.3.2 Problem formulation 209
6.3.3 Analysis conducted 210
6.3.4 Results and discussion 213
6.4 Summary and conclusions 250

CHAPTER 7 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS 253

7.1 Summary & Conclusions 253
7.2 Recommendations for future work 255
7.3 Published and accepted papers 257

CHAPTER 8 REFERENCES 259

List of Appendices

Appendix A: ACO-PPMSO source code and sample input files 273
Appendix B: 21-unit case study results 284
Appendix C: 22-unit case study results 313
Appendix D: 5-station hydropower system results 342

List of Figures

Figure 2.1: Objectives of power plant maintenance scheduling optimisation 6

Figure 2.2: Optimisation methods adopted previously for PPMSO...................................... 16

Figure 2.3: Typical Simulated Annealing (SA) algorithm.. 25

Figure 2.4: Typical Tabu Search (TS) algorithm 27

Figure 2.5: Typical simple genetic algorithm 30

Figure 3.1: Path from nest to food source 41

Figure 3.2: Illustration of the ants' foraging behaviour 44

Figure 3.3: Ant-System-based algorithmic framework.. 53

Figure 4.1: Proposed ACO-PPMSO graph 76

Figure 4.2: Proposed ACO-PPMSO algorithm... 77

Figure 4.3: Local search framework for ACO-PPMSO algorithm 84

Figure 4.4: Stage-1 selection process 90

Figure 4.5: Handling of constraint 1 90

Figure 4.6: Handling of constraint 2 91

Figure 4.7: Handling of constraint 3 92

Figure 4.8: Handling of constraint 4 93

Figure 5.1: Original and modified system load for the 21-unit case study 108

Figure 5.2: Modified 22-unit case study system – Weekly system load 112

Figure 5.3: Testing procedure..117

Figures 5.4(a) & (b): Performance of Elitist-Ant System (EAS) in solving the original 21-unit case study with and without heuristic (Comparison of the SSR-values associated with iteration-best schedules during optimisation run; Best-known SSR = 13.36 x 10^6 MW^2) 127

Figures 5.4(c) & (d): Performance of Elitist-Ant System (EAS) in solving the original 21-unit case study with and without heuristic (Comparison of the violation of constraints associated with iteration-best schedules and infeasibility ratio during optimisation run)...127

Figures 5.5(a) & (b): Performance of Max-Min Ant System (MMAS) in solving the original 21-unit case study with and without heuristic (Comparison of the SSR-values associated with iteration-best schedules during optimisation run; Best-known SSR = 13.36 x 10^6 MW^2). 129

Figures 5.5(c) & (d): Performance of Max-Min Ant System (MMAS) in solving the original 21-unit case study with and without heuristic (Comparison of the violation of constraints associated with iteration-best schedules and infeasibility ratio during optimisation run). 129

Figures 5.6(a) & (b): Performance of Elitist-Ant System (EAS) in solving the original 22-unit case study with and without heuristic (Comparison of the LVL-values associated with iteration-best schedules during optimisation run; Best-known LVL = 52.06 MW). 131

Figures 5.6(c) & (d): Performance of Elitist-Ant System (EAS) in solving the original 22-unit case study with and without heuristic (Comparison of the violation of constraints associated with iteration-best schedules and infeasibility ratio during optimisation run). 131

Figures 5.7(a) & (b): Performance of Max-Min Ant System (MMAS) in solving the original 22-unit case study with and without heuristic (Comparison of the LVL-values associated with iteration-best schedules during optimisation run; Best-known LVL = 52.06 MW). 133

Figures 5.7(c) & (d): Performance of Max-Min Ant System (MMAS) in solving the original 22-unit case study with and without heuristic (Comparison of the violation of constraints associated with iteration-best schedules and infeasibility ratio during optimisation run). 133

Figures 5.8(a) & (b): Performance of Elitist-Ant System (EAS) in solving the modified 21-unit case study with and without heuristic (Comparison of the SSR- and total duration shortened values associated with iteration-best schedules during optimisation run; Best-known SSR = 2.62 x 106 MW2 with 5-week deferral). 135

Figures 5.8(c) & (d): Performance of Elitist-Ant System (EAS) in solving the modified 21-unit case study with and without heuristic (Comparison of the violation of constraints associated with iteration-best schedules and infeasibility ratio during optimisation run). 135

Figures 5.9(a) & (b): Performance of Max-Min Ant System (MMAS) in solving the modified 21-unit case study with and without heuristic (Comparison of the SSR- and total duration shortened values associated with iteration-best schedules during optimisation run; Best-known SSR = 2.62 x 106 MW2 with 5-week deferral). 137

Figures 5.9(c) & (d): Performance of Max-Min Ant System (MMAS) in solving the modified 21-unit case study with and without heuristic (Comparison of the violation of constraints associated with iteration-best schedules and infeasibility ratio during optimisation run). 137

Figures 5.10(a) & (b): Performance of Elitist-Ant System (EAS) in solving the modified 22-unit case study with and without heuristic (Comparison of the LVL- and total duration shortened values associated with iteration-best schedules during optimisation run; Best-known SSR = 101.791 MW with 8-week shortening). 139

Figures 5.10(c) & (d): Performance of Elitist-Ant System (EAS) in solving the modified 22-unit case study with and without heuristic (Comparison of the violation of constraints associated with iteration-best schedules and infeasibility ratio during optimisation run). 139

Figures 5.11(a) & (b): Performance of Max-Min Ant System (MMAS) in solving the modified 22-unit case study with and without heuristic (Comparison of the LVL- and total duration shortened values associated with iteration-best schedules during optimisation run; Best-known SSR = 101.791 MW with 8-week shortening). 141

Figures 5.11(c) & (d): Performance of Max-Min Ant System (MMAS) in solving the modified 22-unit case study with and without heuristic (Comparison of the violation of constraints associated with iteration-best schedules and infeasibility ratio during optimisation run). 141

Figure 5.12: Infeasible local solutions obtained using *PPMSO-2-opt* (original 21-unit case study using EAS) 145

Figure 5.13: Infeasible local solutions obtained using *PPMSO-2-opt* (original 21-unit case study using MMAS) 145

Figure 5.14: Infeasible local solutions using *PPMSO-2-opt* (original 22-unit case study using EAS).....146

Figure 5.15: Infeasible local solutions using *PPMSO-2-opt* (original 22-unit case study using MMAS).....146

Figure 5.16: Infeasible local solutions using *PPMSO-2-opt* (modified 21-unit case study using EAS).....147

Figure 5.17: Infeasible local solutions using *PPMSO-2-opt* (modified 21-unit case study using MMAS).....147

Figure 5.18: Infeasible local solutions using *PPMSO-2-opt* (modified 22-unit case study using EAS).....148

Figure 5.19: Infeasible local solutions using *PPMSO-2-opt* (modified 22-unit case study using MMAS).....148

Figure 5.20: Comparison between results obtained using other optimisation methods (Aldridge *et al.*, 1999; Dahal *et al.*, 1999; Dahal *et al.*, 2000) and the ACO algorithms used in this thesis.....151

Figure 5.21: The (a) maintenance schedule of the 21-unit case study best-found-SSR solution A, the associated (b) personpower allocation and (c) reserve capacity levels.....153

Figure 5.22: The (a) maintenance schedule of the 21-unit case study best-found-SSR solution B, the associated (b) personpower allocation and (c) reserve capacity levels.....154

Figure 5.23: Comparison of reserve levels obtained using ACO, implicit enumeration (Escudero *et al.*, 1980) and tabu search (El-Amin *et al.*, 2000).....155

Figure 5.24: Best-known (a) schedule and (b) the associated generation reserve levels for the 22-unit case study.....156

Figure 5.25: A near best-known (a) schedule and (b) the associated generation reserve levels for the 22-unit case study.....157

Figure 5.26: The (a) maintenance schedule of the modified 21-unit case study best-found-SSR solution A, the associated (b) personpower allocation and (c) reserve capacity levels.....159

Figure 5.27: The (a) maintenance schedule of the modified 21-unit case study best-found-SSR solution B, the associated (b) personpower allocation and (c) reserve capacity levels.....160

Figure 5.28: (a) Maintenance schedule A associated with the best-found OFC for the modified 22-unit case study and (b) the associated generation reserve levels.....161

Figure 5.29: (a) Maintenance schedule B associated with the best-found OFC for the modified 22-unit case study and (b) the associated generation reserve levels.....162

Figure 6.1: Geographical location of Tasmania.....166

Figure 6.2: Schematic diagram of the five-station hydropower system.....166

Figure 6.3: Forecasted system demand for 2006.....169

Figure 6.4: Handling of constraints 1 and 2.....170

Figure 6.5: Dry year storage inflows.....174

Figure 6.6: Intermediate year storage inflows.....174

Figure 6.7: Wet year storage inflows.....174

Figure 6.8: Experimental procedure for the five-station hydropower plant maintenance scheduling optimisation case study 176

Figure 6.9: (a) The best-OFC schedule for wet inflow conditions and (b) the associated unserved energy and spillage conditions 179

Figure 6.10: (a) The best-OFC schedule for intermediate inflow conditions and (b) the associated unserved energy and spillage conditions................................. 180

Figure 6.11: (a) The best-OFC schedule for dry inflow conditions and (b) the associated unserved energy and spillage conditions 181

Figure 6.12: (a) IB-OFC and (b) IB-ETFEIS associated with iteration-best schedules recorded throughout the ACO run that produced the schedule in Figure 6.9 (wet inflow condition)... 182

Figure 6.13: (a) IB-OFC, (b) IB-EUE and (c) IB-ETFEIS associated with iteration-best schedules recorded throughout the ACO run that produced the schedule in Figure 6.10 (intermediate inflow condition) 184

Figure 6.14: (a) IB-OFC, (b) IB-EUE and (c) IB-ETFEIS associated with iteration-best schedules recorded throughout the ACO run that produced the schedule in Figure 6.11 (dry inflow condition)... 186

Figure 6.15: Schedule obtained by engineering judgment.. 188

Figure 6.16: The best-*OFC* schedule for the wet year (EUE = 0 GWh; ETFEIS = 4718 GWh) 190

Figure 6.17: The best-OFC schedule for the intermediate year (EUE = 0 GWh; ETFEIS = 2539 GWh) 190

Figure 6.18: The best-OFC schedule for the dry year (EUE = 0 GWh; ETFEIS = 544 GWh)... 191

Figure 6.19: (a) IB-OFC and (b) IB-ETFEIS associated with iteration-best schedules recorded throughout the ACO run that produced the maintenance schedule shown in Figure 6.16 (wet inflow condition).................................... 192

Figure 6.20: (a) IB-OFC, (b) IB-ETFEIS and (c) IB-DurCuttot associated with iteration-best schedules recorded throughout the ACO run that produced the maintenance schedule shown in Figure 6.17 (intermediate inflow condition) 195

Figure 6.21: (a) IB-OFC, (b) IB-EUE, (c) IB-ETFEIS and (d) IB-DurCuttot associated with iteration-best schedules recorded throughout the ACO run that produced the maintenance schedule shown in Figure 6.18 (dry inflow condition) 197

Figure 6.22: Forecasted 2006 daily average demand for Hydro Tasmania case study 206

Figure 6.23: Historical total system inflows for 2001 ~ 2005 (monthly average)................ 207

Figure 6.24: Optimisation runs for Hydro Tasmania system.. 210

Figure 6.25: The ACO schedule-A (plotted) 227

Figure 6.26: The Hydro schedule (plotted).. 230

Figure 6.27: Difference between Lake Gordon end-of-month energy in storage (%FSL) associated with ACO and Hydro schedules 237

Figure 6.28: Objective function cost associated with iteration-best schedules (a) Iterations 1 to 100 and (b) Iterations 41 to 100 239

Figure 6.29: Averaged expected unserved energy (IB-EUEavg) associated with iteration-best schedules 240

Figure 6.30: Averaged violation of reliability constraints (IB-ResVioavg) associated with iteration-best schedules 240
Figure 6.31: Averaged total reduction in maintenance duration due to shortening and deferral (IB-DurCutavg) associated with iteration-best schedules 241
Figure 6.32: Averaged expected total final energy in storage (IB-ETFEISavg) associated with iteration-best schedules 241
Figure 6.33: Infeasibility ratio for scenario-A runs 242
Figure 6.34: IB-OFC curve for scenario-B run 243
Figure 6.35: IB-ResVio and IB-ETFEIS for scenario-B run 243
Figure 6.36: IB-OFC for scenario-B run (considering shortening and deferral) 244
Figure 6.37: IB-ResVio and IB-DurCut for scenario-B run (considering shortening and deferral) 245
Figure 6.38: IB-ETFEIS for scenario-B run (considering shortening and deferral) 245
Figure 6.39: IB-ResVio and IB-ETFEIS for scenario-C run 247
Figure 6.40: IB-OFC for scenario-D run 249
Figure 6.41: IB-ResVio and IB-ETFEIS for scenario-D run 249
Figure 6.42: IB-dev for scenario-D run 250

List of Tables

Table 2.1: Summary of optimisation methods for PPMSO 36

Table 3.1: Pheromone intensity updated on paths 44

Table 3.2: A summary of the distinguishing features of the ACO algorithms discussed 59

Table 4.1: Adaptations for Eq. 4.9 in stages 1, 2 and 3 of the selection process 79

Table 5.1: Details of 21-unit system (Aldridge *et al.*, 1999) 100

Table 5.2: Details of 22-unit system (Escudero *et al.*, 1980) 104

Table 5.3: Weekly peak load of the 22-unit system (El-Amin *et al.*, 2000) 105

Table 5.4: Personpower utilization for the modified 21-unit case study system 109

Table 5.5: Details of the modified 22-unit system 114

Table 5.6: Results for the 21-unit unit problem instance given by Elitist-Ant System (EAS) [deviation from best-known OFC of $13.66M] 118

Table 5.7: Results for the 21-unit unit problem instance given by Max-Min Ant System (MMAS) [deviation from best-known OFC of $13.66M] 118

Table 5.8: Results for the 22-unit unit problem instance given by Elitist-Ant System (EAS) [deviation from best-known OFC of $52.06] 119

Table 5.9: Results for the 22-unit unit problem instance given by Max-Min Ant System (MMAS) [deviation from best-known OFC of $52.06M] 119

Table 5.10: Results for the Modified 21-unit unit problem instance given by Elitist-Ant System (EAS) [deviation from best-known OFC of $15.71M] 120

Table 5.11: Results for the Modified 21-unit problem instance given by Max-Min Ant System (MMAS) [deviation from best-known OFC of $15.71M] 120

Table 5.12: Results for the Modified 22-unit unit problem instance given by Elitist-Ant System (EAS) [deviation from best-known OFC of $916.12] 121

Table 5.13: Results for the Modified 22-unit unit problem instance given by Max-Min Ant System (MMAS) [deviation from best-known OFC of $916.12] 121

Table 5.14: Impact of the new heuristic formulation with and without using local search 122

Table 5.15: Impact of *PPMSO-2-opt* local search operator with and without heuristic 143

Table 5.16: Impact of *Duration Extender* local search operator with and without heuristic 143

Table 6.1: Power station and headwater data 167

Table 6.2: Details of maintenance tasks 168

Table 6.3: Results given by ACO-PPMSO for different inflow conditions investigated 177

Table 6.4: Comparison of results obtained by different methods 188

Table 6.5: Results obtained by different methods 199

Table 6.6: Fixed-date maintenance tasks 201

Table 6.7: Maintenance tasks that need to be scheduled 201
Table 6.8: Storage levels on 1 Jan 2006 208
Table 6.9: Parameters for optimisation runs 213
Table 6.10: Summary of results for the Full Hydro Tasmania case 214
Table 6.11: The schedules proposed by ACO (^) and Hydro Tasmania (^^) 215
Table 6.12: Objective values and constraint satisfaction associated with the ACO and the Hydro schedules 234
Table 6.13: Levels of major storages at the end of planning horizon associated with the ACO and Hydro schedules 235
Table 6.14: Affected maintenance tasks as a result of increased system demand 246
Table 6.15: Summary of the utility of two different schedules obtained by ACO-PPMSO for scenario C 246
Table 6.16: Revised start dates as a result of the late return of the Tungatinah station 248

Glossary of Selected Acronyms and Notation

Acronyms

ACO	Ant Colony Optimisation
ACS	Ant Colony System
AS	Ant System
AS_{rank}	Rank-Based Ant System
DP	Dynamic programming
$DurCut_{tot}$	total reduction in maintenance duration due to shortening and deferral
EAS	Elitist-Ant System
EFEIS	Expected final energy in storage of a lake
EUE	Expected unserved energy
ETFEIS	Expected total final energy in storage of a power system
GA	Genetic algorithm
GNGA	Generational genetic algorithm
GSP	Group-shop scheduling problem
HCF	Hyper-Cube Framework for ACO
IB	Iteration-best
IP	Integer programming
LOLP	Lost of load probability
LP	Linear programming
LVL	the summed deviation of generation reserve from the average reserve over the entire planning horizon
MIP	Mixed integer programming

MMAS	Max-Min Ant System
OFC	Objective function cost
PPMSO	Power plant maintenance scheduling optimisation
RCPSP	Resource-constrained project scheduling problem
ResVio	violation of reserve constraints
SA	Simulated annealing
SMTWTP	Single-machine total weighted tardiness scheduling problem
SSGA	Steady state genetic algorithm
SSR	Sum of squares of the reserve generation capacity in each week
TS	Tabu search
TSP	Travelling Salesman Problem
WDS	Design of water distribution system

Notation

α and β	relative importance of pheromone intensity and the heuristic, respectively
$chdur_n$	chosen maintenance duration for task d_n
$D = \{d_1, d_2, \ldots, d_N\}$	finite set of N maintenance tasks to be scheduled
$\Delta\tau_*(t)$	amount of pheromone rewarded to pheromone trail τ_* by the end of iteration t
ear_n	the earliest time for maintenance task d_n to begin
f	objective function which assigns an objective function value $f(s)$ to each trial maintenance schedule s
f_{ews}	factor of load demand required for reserve
η	heuristic value

L_t	anticipated load for period t
lat_n	the latest time for maintenance task d_n to end
m	size of an ant population
$NormDur_n$	normal (default) duration of maintenance task d_n
$f(s)$ *or* $OFC(s)$	objective function cost associated with maintenance schedule s
Ω	set of constraints
P_n	loss of generating capacity associated with maintenance task d_n
p_{best}	probability that the paths of the current iteration-best-solution will be selected, given that non-iteration best-options have a pheromone level of τ_{min} and all iteration-best options have a pheromone level of τ_{max}.
$p_{n,opt}(t)$	probability that decision path *opt* is chosen for maintenance of task d_n in iteration t
ψ	infeasibility ratio
$ResAvai_t^r$	associated capacity of resource of type r available at period t
$Res_{n,k}^r$	amount of resource of type r available that is required by task d_n at period k
S	set of all maintenance schedules
S^*	set of globally optimal maintenance schedules
$start_n$	maintenance start time chosen for task d_n
s_n	time step considered for maintenance duration shortening for task d_n
s	a trial maintenance schedule
T_{plan}	the planning horizon
τ_0	initial pheromone trail intensity
τ	pheromone trail intensity
τ_{min}, τ_{max}	lower and upper limits of pheromone trail
$X_{n,t}$	Binary variables, which can take on values 0 or 1, are used to represent the state of a maintenance task in a given time period t