CHAPTER 8

RESULTS AND CONCLUSIONS

8.1 INTRODUCTION

The maintenance of water distribution systems is a complex task encompassing a wide range of alternatives. This study demonstrates the application of four Stochastic Search Algorithms viz., Simulated Annealing, Tabu Search technique, a Genetic Algorithm with Monte Carlo based crossover scheme (MCGA) and a Genetic Algorithm with Orthogonal Array based crossover scheme (OAGA) to determine the cost-effective maintenance strategy for a real-life Velachery Water Distribution System, at Chennai, India. The measure of performance considered in order to evaluate the various WDS maintenance strategies is the total discounted maintenance cost over the specified planning horizon subject to the WDS availability constraint. In this chapter, the results obtained from the proposed search algorithms are given in Section 8.2. The conclusions of the study are given in Section 8.3. The scope for further study is presented in Section 8.4.

8.2 WDS MAINTENANCE OPTIMIZATION – RESULTS

The results obtained from the present study provide insights into the working of the proposed Stochastic Search Algorithms viz. Simulated Annealing technique, Tabu Search approach and Genetic algorithms and their application to solve water distribution system maintenance problems. The best objective function values, $Z^*$ and the maximum availability that could be
achieved by implementing proposed maintenance strategy for the various stochastic search algorithms used in the WDS maintenance optimization study are presented in Table 8.1.

Table 8.1 WDS Maintenance Optimization – Results

<table>
<thead>
<tr>
<th>Search Algorithm</th>
<th>Total Cost, Z* (Rs. X10^6)</th>
<th>Maximum Availability achieved</th>
<th>Ineffective utilization time per year (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated Annealing</td>
<td>4.559</td>
<td>0.9302</td>
<td>25.5</td>
</tr>
<tr>
<td>Tabu Search</td>
<td>4.673</td>
<td>0.9134</td>
<td>31.6</td>
</tr>
<tr>
<td>MCGA</td>
<td>4.566</td>
<td>0.9247</td>
<td>27.5</td>
</tr>
<tr>
<td>OAGA</td>
<td>4.528</td>
<td>0.9285</td>
<td>26.1</td>
</tr>
</tbody>
</table>

It is found from Table 8.1 that among the various search algorithms proposed to solve the WDS maintenance optimization problem under study, Genetic Algorithm with Orthogonal Array based crossover scheme (OAGA) is found to be quite effective in rendering superior-quality solution with respect to minimizing the total discounted maintenance cost of WDS over the maintenance planning horizon. The proposed search algorithms are coded in C++ and executed on a personal computer with Pentium 4– 2.4 GHz processor and 760 MB RAM.

The ineffective utilization time of WDS when maintenance strategies are not adopted is estimated to be 56.8 days per year (for 84.45% availability) with a total unscheduled discounted maintenance cost of Rs.5.398 x 10^6. The maintenance strategy obtained from the proposed Simulated Annealing algorithm when implemented can reduce the WDS ineffective utilization time to 25.5 days per year (93.02% availability) with a relatively less cost. It is observed that the implementation of the proposed maintenance strategy (from Simulated Annealing algorithm) for the existing
water distribution system can bring 8.57% of improvement in system availability. And the number of ineffective utilization time is reduced by 31.3 days per year. The search algorithms-derived maintenance strategies are promising and competitive and can be effectively used for water distribution system maintenance.

In general, a comparison of the Stochastic Search Algorithms viz., Simulated Annealing, Tabu Search and Genetic Algorithms is difficult as they are not well-defined algorithms but rather schemes of algorithms. The comparison of the search effectiveness of the proposed search algorithms are shown in Figure 8.1 to Figure 8.3. It is clear from Figure 8.1 and Figure 8.2 that OAGA yielded good quality solutions and outperformed the other algorithms with respect to minimizing the objective function value, $Z^*$. From Figure 8.2 and Figure 8.3, it is found that Simulated Annealing algorithm has the potential to produce good solution with respect to maximizing the WDS availability value and minimizing the total ineffective utilization time. It is also observed that among the four proposed search algorithms, Tabu Search could not yield a better quality solution for this maintenance optimization problem.

![Figure 8.1 Search Effectiveness of Search Algorithms with respect to $Z^*$](image)
Figure 8.2 Search Effectiveness of Search Algorithms with respect to WDS Availability

Figure 8.3 Search Effectiveness of Search Algorithms with respect to WDS Ineffective Utilization Time
Figure 8.4 shows the comparison of the computational effort of the search algorithms. It is observed that OAGA takes a considerable computational effort in terms of number of iterations as well as the time needed to search for the best solution. The study revealed that Simulated Annealing technique has successfully searched for solutions to the maintenance optimization problem with less computational effort.

Figure 8.4 Computational Effort of Search Algorithms

In this study, a procedure of Random Search algorithm is used to prove the search effectiveness of the proposed SA, TS and GA search techniques. This algorithm is presented below:

8.2.1 Random Search Algorithm

In order to compare the performance of Simulated Annealing, Tabu Search and Genetic Algorithms for the WDS maintenance optimization problem, a random search algorithm is used. The procedure adopted is given below:
Step 1: The maximum CPU time taken by SA, TS and GA search methods for the same maintenance problem is made available.

Step 2: Choose a solution S randomly.

Step 3: Invoke WDS simulation model and compute the objective function value $Z$.

Step 4: Update the best objective function value, $Z^*$. 

Step 5: If total CPU time is less than that of maximum CPU time taken by SA, TS and GA for the same problem, go to Step 2 else go to Step 6.

Step 6: Report $Z^*$ and the CPU time.

The results of the Random Search Algorithm obtained for different CPU times are given in Table 8.2.

<table>
<thead>
<tr>
<th>Computational Effort (CPU seconds)</th>
<th>$Z^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>5.431</td>
</tr>
<tr>
<td>140</td>
<td>5.184</td>
</tr>
<tr>
<td>210</td>
<td>4.957</td>
</tr>
<tr>
<td>280</td>
<td>4.823</td>
</tr>
<tr>
<td>350</td>
<td>4.808</td>
</tr>
</tbody>
</table>

The solution quality obtained from the Random Search Algorithm for the same computational effort taken by the proposed Stochastic Search Algorithms is found to be very poor. This local-search approach could not yield a better solution even when the algorithm is run for twice the
computational time used in the Stochastic Search Algorithms applied to the same WDS maintenance optimization problem. It is found that the quality of solutions obtained by the proposed Simulated Annealing algorithm, Tabu Search algorithm and Genetic algorithms employed is much better than the solutions obtained from the local Random Search algorithm for the given WDS maintenance problem under study.

8.3 CONCLUSIONS

In this study, a maintenance decision model to aid the water management experts select the best maintenance strategy which maximizes the water distribution system infrastructure availability at least cost is proposed. The application of the proposed stochastic search techniques viz., Simulated Annealing algorithm, Tabu Search approach and Genetic algorithms to solve the maintenance optimization problem in a real-life water distribution system has been demonstrated. Monte Carlo simulation approach is employed taking into account the failure characteristics of pipe network and the pumping components to compute the WDS availability.

The test problems chosen by researchers in the past to evaluate the WDS maintenance models are well known virtual water distribution networks taken from the literature. They do not represent the actual conditions existing in the real-life water distribution systems. But in this research study an existing water distribution system in Velachery, at Chennai, India is considered. The results obtained from the proposed Stochastic Search Algorithms employed for the water distribution system in the study would greatly benefit the water management experts for improving the performance (infrastructure availability) of the water distribution system. The study showed that the infrastructure availability value of the existing water distribution system can be increased from 84.45% to 93.02% when the near-optimal maintenance strategy proposed by Simulated Annealing algorithm is
implemented. The results of the proposed Stochastic Search Algorithms should provide guidance to the decision makers and must be fine-tuned to an acceptable engineering plan.

8.4 SCOPE FOR FURTHER STUDY

The proposed Stochastic Search Algorithms implemented on the WDS maintenance optimization study yielded good-quality solutions. Nevertheless, it must be pointed out that there is no proof that any of the solutions given by these optimization algorithms provide global optimality relative to the optimal maintenance of water distribution systems. Improvements in the solution quality are possible, while conceptually better search algorithms can be tested. New evolutionary algorithms such as Ant Colony Optimization, Particle Swarm Optimization and Honey Bee Mating optimization can be proposed in future to obtain better solutions.

Failure Modes and Effect Analysis has been carried out in this study to determine the potential failure modes of the water distribution system. A more detailed failure analysis of WDS with other failure modes such as pipe corrosion and valve failure together with the common-cause failures and the failure modes interaction effects can be studied. Moreover, the times between failures of the components in the WDS are assumed to follow exponential distribution (wherein the failure rate is assumed to be a constant). But the deteriorating components in the system may assume variable failure rates and therefore the application of a suitable failure time distribution can be explored.

Any changes in the water distribution system configuration such as the use of different pipe materials in the distribution network and the replacement of pumping system components with higher reliability can be considered in the study and their effects on the WDS infrastructure
availability and the total discounted cost can be studied. Also it is possible to extend this work by considering the hydraulic reliability of the pipe network taking into account the failures resulting from hydraulic causes. Other rehabilitation and repair strategies can be incorporated in the study and their effects on the best solution for system performance can be analyzed. The optimal maintenance strategy when adopted can ensure uninterrupted supply of water to the consumers, but may fail in supplying water of desired quality. These limitations of the study can be addressed in future.