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MULTI-OBJECTIVE PIPE SMOOTHING GENETIC ALGORITHM FOR WATER DISTRIBUTION NETWORK DESIGN

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This paper describes the formulation of a Multi-objective Pipe Smoothing Genetic Algorithm (MOPS-GA) and its application to the least cost water distribution network design problem. Evolutionary Algorithms have been widely utilised for the optimisation of both theoretical and real-world non-linear optimisation problems, including water system design and maintenance problems. In this work we present a pipe smoothing based approach to the mutation of chromosomes which utilises engineering expertise with the view to increasing the performance of the algorithm whilst promoting engineering feasibility within the population of solutions. MOPS-GA is based upon the standard Non-dominated Sorting Genetic Algorithm-II (NSGA-II) and incorporates a modified mutation operator which directly targets elements of a network with the aim to increase network smoothness (in terms of progression from one diameter to the next) using network element awareness and an elementary heuristic. The pipe smoothing heuristic used in this algorithm is based upon a fundamental principle employed by water system engineers when designing water distribution pipe networks where the diameter of any pipe is never greater than the sum of the diameters of the pipes directly upstream resulting in the transition from large to small diameters from source to the extremities of the network. MOPS-GA is assessed on a number of water distribution network benchmarks from the literature including some real-world based, large scale systems. The performance of MOPS-GA is directly compared to that of NSGA-II with regard to solution quality, engineering feasibility (network smoothness) and computational efficiency. MOPS-GA is shown to promote both engineering and hydraulic feasibility whilst attaining good infrastructure costs compared to NSGA-II.

INTRODUCTION

Evolutionary Algorithms (EAs) are widely used for the optimisation of both theoretical and real-world problems. These problems tend to be highly complex and are commonly comprised of multiple objectives and constraints which limit the feasible space to be searched. One such problem is that of optimising a water distribution network where the task is to determine the optimally least-cost network design that still meets the requirements of the network (typically the provision of the required pressure at each of the points of demand). EAs have been shown to be excellent tools for optimising such networks, but most formulations do not incorporate engineering expertise into the optimisation. As such, the solutions they propose can be excellent from an objective function perspective, but are not able to be implemented in the real-world without considerable modification.

Building upon our previous work [1], we utilise a heuristic based approach for the mutation of chromosomes based on human engineering knowledge and demonstrate this method on a number of multi-objective water distribution network design problems. The heuristic-based 'pipe smoothing' approach is shown to perform better than a standard Multi-objective Evolutionary Algorithm (NSGA-II) on all water distribution network design problems tested, both in terms of engineering feasibility and performance.

MULTI-OBJECTIVE PIPE SMOOTHING GENETIC ALGORITHM

The Multi-Objective Pipe Smoothing Genetic Algorithm (MOPS-GA) is based around the principle that in a water distribution network (WDN) the diameter of any pipe is never greater than the sum of the diameter(s) of the directly upstream pipes. Networks that adhere to this rule can be seen to 'smoothly' transition from large to small diameters from source to the extremities of the network. This rule is routinely and implicitly applied by engineers when designing such networks as it makes little sense to follow a smaller diameter pipe with a larger one in the majority of circumstances. The larger pipe will cost more to install and will not add to the hydraulic capability of the system as it will be constrained by the smaller diameter pipe upstream. One further negative aspect of this arrangement is that velocities will be lower in the larger pipe and high water age can become an issue. A standard Multi-Objective Genetic Algorithm (MOGA) of course will mutate some of these conflicting pipe selections from the final solution as they have a corresponding improvement in the cost function and no hydraulic penalty. However in the case of larger networks extensive experimentation has shown that even well-optimised solutions after hundreds of thousands of generations of a standard EA still contain significant numbers of incorrectly sized pipes.

MOPS-GA applies the rule described above directly to the genotype without evaluating the effect this process has on the phenotype (and therefore incurring additional computational cost). The heuristic employed by MOPS-GA is developed from the network topology of a specific problem and remains constant throughout the evolutionary process. The heuristic is applied to a solution through the mutation operator; where the probability of the heuristic being applied is defined by a preset algorithm parameter. It is the aim of the heuristic to guide the algorithm's search to the engineering feasible solution space to locate smoother WDN designs whilst maintaining the performance of a standard MOGA. The MOPS-GA mutation operator does not perform any additional partial or full fitness evaluations, except a single hydraulic simulation at initialisation to determine flow directions. This was an important consideration when developing MOPS-GA as additional fitness evaluations would require further hydraulic evaluations, increasing algorithm run time.

MOPS-GA is in essence a standard version of the Non-dominating Sorting Genetic Algorithm-II (NSGA-II) [2] which incorporates an additional feature; a pipe smoothing heuristic based mutation operator. NSGA-II was used with tournament selection with tournament size t and single-point crossover with probability c. A binary string comprised of N sub-strings was employed where each sub-string represents the diameter of each pipe in the WDN. Mutation was conducted as a random bitwise mutation with probability m.

Pipe Smoothing Mutation Operator

The pipe smoothing mutation operator randomly selects a pipe to be mutated. The sum of all the diameters of the directly upstream pipes is set as the maximum allowable diameter the current pipe can be. This operator also employs a skewed roulette wheel approach to the random selection of the pipe diameter. Whereby the larger pipe diameters that fall within the maximum allowable size are assigned a higher probability of selection to prevent the algorithm from tending towards under-sizing of the network. Upon selection the pipe being mutated is changed to the selected diameter.

To function correctly both the pipe smoothing initialiser and mutation operator require each pipe in the network to be ‘aware’ of the pipes directly up and down stream of their location. When changes are made to a WDN there is a possibility that flow direction could change in some pipes hence swapping up & down stream pipes relative to the pipe in question. The flow direction is logged at each hydraulic evaluation of the network, therefore to preserve this hydraulic data the pipe smoothing mutation operator precedes the crossover operator.

COMPUTATIONAL RESULTS

MOPS-GA was implemented in C++ and run on an Intel Core i7-4770K PC. The test problems used to evaluate the algorithm including a number of benchmark networks from the literature. The majority of the following test cases can be found at *http://emps.exeter.ac.uk/engineering/research/cws/resources/benchmarks/*. In all test cases both MOPS-GA and NSGA-II are run using identical common parameters.

To enable the comparison of MOPS-GA and NSGA-II the hypervolume [3] indicator was employed. The hypervolume indicator allows the tracking of algorithm convergence and provides a measurement of population diversity. Note that the hypervolume values are normalised from 0 to 1 using the theoretical best (utopia) and worst (nadir) points in the solution space.

Hanoi

MOPS-GA was applied to the Hanoi problem; a single reservoir, gravity fed water distribution network which consists of 32 junctions and 34 pipes arranged in a triple loop formation. The probability that the pipe smoothing mutation operator was employed was varied throughout a number of experiments to assess the influence the modified operator had on the performance of the algorithm. When the pipe smoothing mutation operator was not employed, the standard bitwise mutation operator was used instead.

The base algorithm used in the following runs was built on a standard configuration of the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) with a mutation rate of 0.01 and tournament size of 0.05N where N is the population size which in this case is 100. These parameters were selected based on previous experimentation to ensure NSGA-II is running at peak (or close to) performance. The probability of Pipe Smoothing Mutation (PSM) was varied between 0% and 100% at 25% intervals. For each parameter set the algorithm was run a total of 30 times for 100,000 solution evaluations. Below are the average results from these experiments.

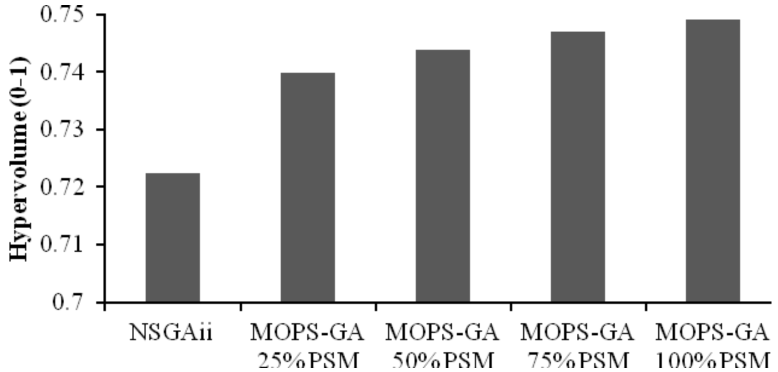

Figure 1. Hypervolume results for the Hanoi Problem

Figure 1 shows the comparison between NSGA-II and MOPS-GA with varying application probability (25%-100%) of the Pipe Smoothing Mutation Operator (PSMO). It is clear from these results that the addition of the PSMO improves the final solution quality of the algorithm.

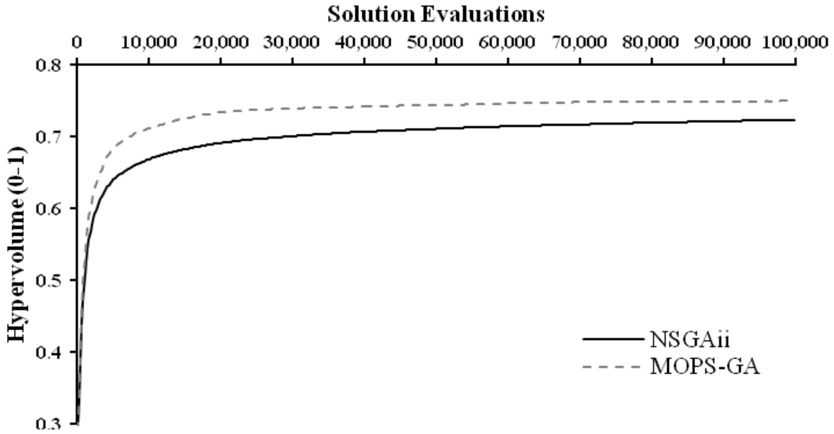

Figure 2. Mean Hypervolume Results over Evaluations for the Hanoi Problem

Figure 2 shows the mean hypervolume from the 30 runs for each algorithm (NSGA-II & MOPS-GA 100% PSM) over 100,000 solution evaluations. MOPS-GA clearly exhibits a much faster convergence rate than that of NSGA-II, obtaining a better solution quality in a small number of solution evaluations.

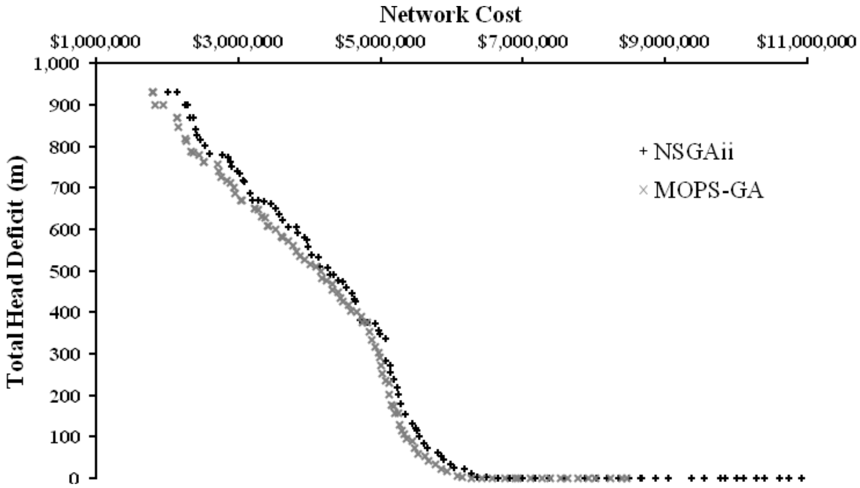

Figure 3. Best Solution Sets for the Hanoi Problem

Figure 3 shows the solution sets produced by both algorithms for a single run after 100,000 solution evaluations. It is apparent from this figure that the majority of the solutions produced by MOPS-GA dominate those generated by NSGA-II, achieving lower network cost whilst obtaining reduced head deficit.

New York Tunnels

The New York Tunnels Problem [4] is a parallel expansion problem consisting of 21existing pipes and 20 junctions fed by a fixed head reservoir. The objective is to find the least cost configuration of pipes that could be installed parallel to the existing pipes to meet the head constraints of the problem. There are 16 available pipe diameters ranging from 0in to 804.0in therefore no encoding redundancy is required when utilizing a standard binary encoding method. The parameters of NSGA-II were tuned to the problem as before. It was found that following parameters achieved the best results for the New York Tunnels Problem: population size (N) of 100, tournament size of 0.05N and probability of mutation of 0.001. As with the Hanoi experiments, the probability of PSMO was varied between 0% and 100% at 25% intervals. Each algorithm variant was run a total of 30 times each for 100,000 solution evaluations.

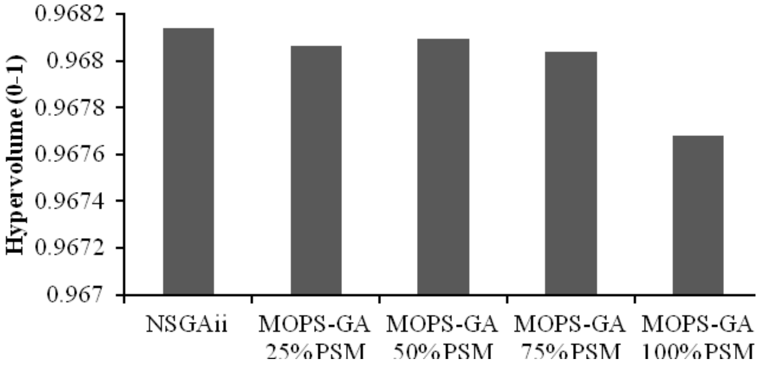

Figure 4. Hypervolume results for the New York Tunnels Problem

From figure 4, the difference between NSGA-II and the MOPS-GA variants appears to be very marginal as there is only a 0.00046 hypervolume difference between the best (NSGA-II) and worst (MOPS-GA 100%PSM) results. This is due to all algorithms having converged on a similar quality of solution. This is made more apparent when comparing the mean hypervolume between NSGA-II and MOPS-GA 50% PSM in figure 5. Both algorithms have converged at roughly the same solution set by approximately 35,000 evaluations; however the MOPS-GA variant displays much faster convergence than that of NSGA-II.

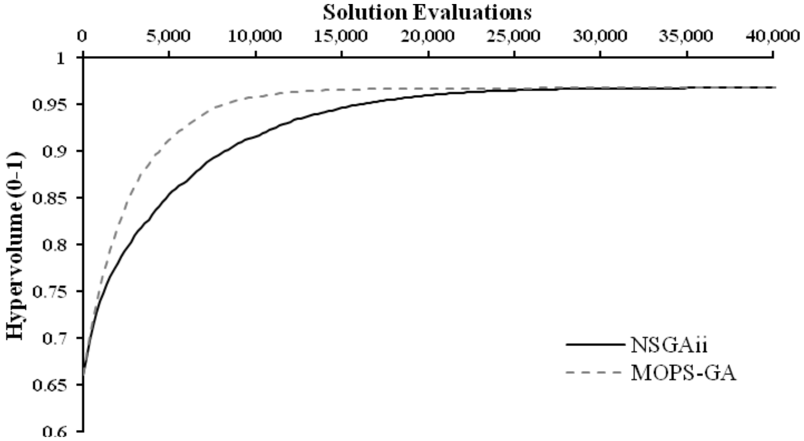

Figure 5. Mean Hypervolume Results over Evaluations for the New York Tunnels Problem

Network B Problem

The Network B Problem [5] is based on a real WDN and consists of 1277 pipes and 1106 junctions, fed by a single fixed head reservoir. 26 pipe diameters are available ranging from 50mm to 999mm. As with the previous problems in this paper, the following parameters were chosen after performing a number of runs to ensure NSGA-II ran at close to peak performance. Both NSGA-II and MOPS-GA were run using the same parameters: population size (N) of 100, tournament size of 0.05N and probability of mutation of 0.001. Due to the complexity and resultant runtime, both NSGA-II and the MOPS-GA variants were only run a total of 10 times each for 200,000 solution evaluations. Figure 6 shows the mean hypervolume obtained by NSGA-II and the MOPS-GA variants.

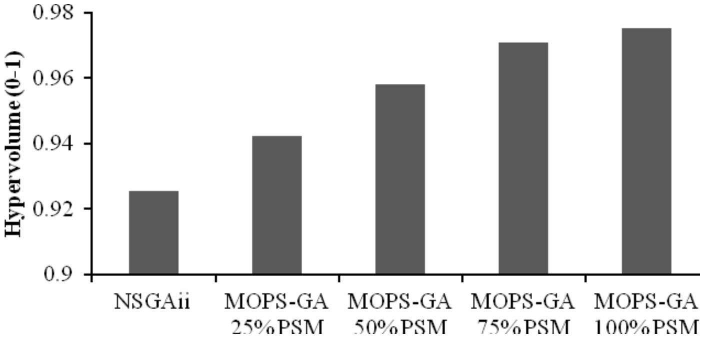

Figure 6. Hypervolume results for the Network B Problem

After 200,000 solution evaluations MOPS-GA (100% PSM) achieves a hypervolume value of 0.975 compared to a value of 0.925 obtained by NSGA-II. In this case the application of the Pipe Smoothing Mutation Operator (PSMO) is shown to have a beneficial effect on the algorithm's search; there is a distinct correlation between the application of the PSMO and resultant solution quality compared to that of NSGA-II.

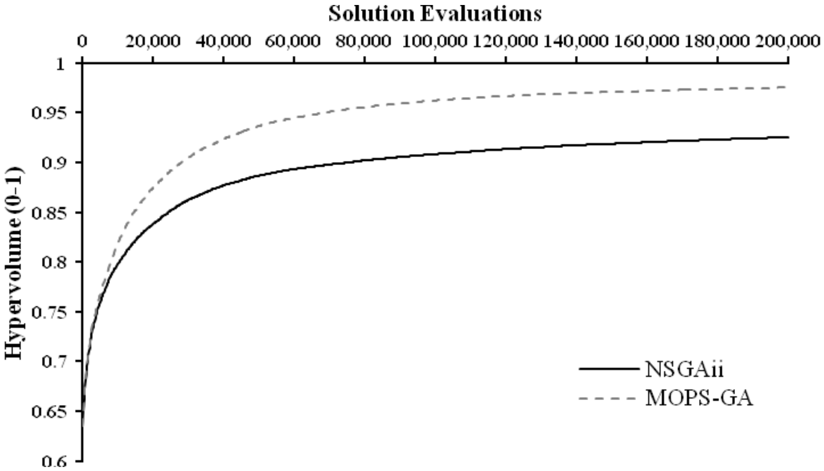

Figure 7. Mean Hypervolume Results over Evaluations for the Network B Problem

Figure 7 shows the mean hypervolume values from the 10 runs for both NSGA-II and MOPS-GA (100% PSM) over the 200,000 solution evaluations. It is apparent from this figure that MOPS-GA outperforms NSGA-II in terms of hypervolume, not only showing a faster rate of initial convergence but also the achievement of a higher quality set of solutions.

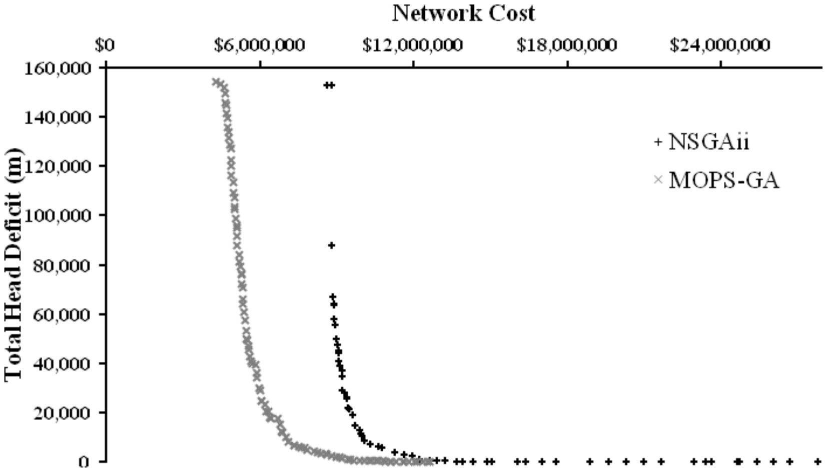

Figure 8. Best Solution Sets for the Network B Problem

Figure 8 shows the solution sets produced by both algorithms for a single run after 200,000 solution evaluations. In this case, the majority of solutions produced by MOPS-GA dominate those of NSGA-II, often finding solutions with a lower cost and smaller head deficit. It is also observed that MOPS-GA tends to promote solutions with higher total head deficit as opposed to solutions with high network cost which seems to be encouraged by NSGA-II. This is an expected trait of MOPS-GA as the Pipe Smoothing Mutation Operator (PSMO) even with the bias towards larger sizes tends to decrease the diameter of the pipe being mutated and therefore restricting flow causing increased hydraulic deficit in downstream junctions.

CONCLUSION

A Multi-objective Pipe Smoothing Genetic Algorithm (MOPS-GA) has been developed and assessed on well-known benchmarks from the literature. Utilising a heuristic, MOPS-GA encodes engineering knowledge into the Non-dominating Sorting Genetic Algorithm - II (NSGA-II) with the view to improving the performance of the algorithm. The influence of the pipe smoothing mutation operator of MOPS-GA has shown to outperform the standard configuration of NSGA-II on all benchmark problems tested in this paper without incurring additional fitness evaluations and hence computational complexity. For all problems tested in this paper, MOPS-GA displayed faster convergence than NSGA-II and achieved a better set of final solutions in all but one of the test problems.

These experiments show MOPS-GA will outperform NSGA-II for a range of benchmark problems, including large networks based on real world systems. Although further, more extensive experiments should be performed to verify the effectiveness of the new algorithm on further real-world networks.

ACNOWLEDGEMENTS

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