International Journal of Core Engineering & Management
Volume-6, Issue-07, 2020 ISSN No: 2348-9510

A NOVEL METHOD FOR OPTIMAL DESIGN OF WATER DISTRIBUTION MAINS USING DARWIN DESIGNER OPTIMIZER IN WATERGEMS HYDRAULIC MODELING TOOL

Tanay Kulkarni
Water Engineering Consultant,
Pune, India,
tanaykulkarni@outlook.com

Sandip Mali
Professor,
Pimpri Chinchwad College of Engineering,
Pune, India,
sandip.mali@pccoepune.org

Abstract

The design of water distribution networks that would satisfy all the requirements per the Central Public Health and Environmental Engineering Organization (CPHEEO) has always been a key challenge to designers and practitioners in India. Aside from other prominent challenges, one significant issue is designing the water network to minimize capital costs. Most of the capital cost in water supply projects consists of water pipes. Thus, optimizing the size of pipes directly results in the optimal capital cost of these projects. Many optimization techniques have been developed and implemented to achieve optimal pipe sizes, which in turn provide optimal capital expenditure (Capex). Since the 1990s, Genetic Algorithms (GA) have gained popularity worldwide. This paper discusses the application of Darwin Designer, a GA-based optimization tool, within a commercially available hydraulic modeling software, WaterGEMS. This study highlights a major practical challenge designers face when using Darwin Designer to design a new water network subdivision while meeting the pressure and flow design requirements. It then proposes a novel methodology to help design the entire water network, including the feeder and distribution mains. The results of this methodology are compared to those of a design procured by the city's consultant.

Keywords : water distribution network, hydraulic model, pipe diameter design, Darwin Designer, WaterGEMS

I. INTRODUCTION

The design of new Water distribution networks (WDN) and the rehabilitation, expansion, and upgrade of existing WDNs will continue to be important challenges, mainly because WDNs continue to age, and infrastructure continues to develop and expand. In a developing country like India, millions of Rupees are spent yearly on laying, rehabilitating, and expanding water distribution networks. Because of numerous design parameters and their combinations, designing WDNs at a minimum cost is very complex. Despite extensive research and the invention of various soft tools, the optimal design that caters to numerous constraints and satisfies basic requirements remains painful and troublesome for practitioners. WDNs transport water from the water treatment facilities to customers. The design of these networks considers the pressurized distribution of water, which is a Newtonian incompressible fluid, from higher to lower energy through closed, filled pipes. These networks are analysed mathematically to better understand the distribution of mass and energy throughout the network. In the past, practitioners used the Hardy Cross method to analyze these networks by balancing energies (head) and flow within every loop. It took time to arrive at convergence, and after many iterations, practitioners could optimally design networks. This was practically impossible for larger, more complex distribution systems that fed water to larger cities. In the 1980s, World Bank-funded simple computer programs were introduced in developing countries to analyze and design WDNs. In the 1990s, the United States Environment Protection Agency (EPA) developed EPANET software to analyze WDNs. It soon gained popularity in the designer community because of its simple, more user-friendly graphical user interface, yet advanced capabilities to solve complex larger networks. Since then, many advanced tools have been developed and widely used to analyze and design WDNs. This study uses hydraulic modelling software – WaterGEMS by Bentley Systems, Inc. Darwin Designer is a tool based on a genetic algorithm for pipe diameter optimization. This studies how this tool often yields a misleading optimal design that results in lesser use of the tool. A case study of the City of Pimpri Chinchwad Municipal Corporation (PCMC) is presented, and a new methodology is presented for using Darwin Designer to arrive at a viable design.

II. LITERATURE REVIEW

A. **Network Resilience:** A work by Prasad and Park (2004) presents a multi-objective genetic algorithm (GA) model to minimize network costs while maximizing network resilience. This resilience is assessed through three measures: minimum surplus head index, total surplus head index, and resilience index. Maximizing these indices enhances the surplus head at junction nodes but may overlook redundancy effects, which can negatively impact downstream nodes. The authors propose a Non-Dominated Sorting Genetic Algorithm (NSGA) that modifies the selection process while maintaining mutation and crossover methods. Their unique constraint-handling technique avoids the need for penalty functions, which can vary across problems. The method demonstrated the effectiveness of network resilience through a set of Pareto-optimal solutions in cost and performance.

B. **Reduction in Search Space by Critical Path Method:** Kadu et al. (2008) suggest selecting a route where the flow becomes concentrated as the path when a demand node has two or more routes with equal minimum lengths. This happens when the network is a grid. It is also noticed in the literature that the path having the steepest available friction slope is the shortest route and corresponds to the cheapest mode of transporting the demand to a node. The HGLs available at every end node of the distribution tree (consisting of primary links) must equal the minimum required HGLs for an optimal solution. The HGLs must be such as:

- They satisfy the nodal HGL constraints.
- They permit the flow along the various links of the distribution tree.
- They are nearer to the optimal values.

This modification in the GA proposed proves to be more efficient and effective in reducing the search space and yields better results.

C. **Dynamically Expanding Choice-Table Approach:** The search space in optimizing Water Distribution Networks (WDN) is typically vast, leading to increased computational time and inefficiency when using traditional Genetic Algorithms (GA) that consider the entire space as equipotential. To address this, Zheng et al. (2011) proposed a new method involving choice tables to reduce the search space. Each decision variable, like pipe diameter, has a choice table of commercially available sizes arranged in ascending order. Only a subset of these sizes is randomly exposed in the initial GA generation. If most solutions select the smallest diameter, further reduction is possible; conversely, a majority choosing the largest indicates a need for an increase. This approach allows for 'self-tailored' choice tables that evolve in later generations. Pipes fixed at extreme sizes are removed as decision variables, enhancing GA's efficiency by focusing on more promising areas. The method was validated using the New York Tunnels Problem, demonstrating performance comparable to other optimization techniques.

D. **Heuristic Hierarchical Approach:** Many researchers have focused on new algorithms for optimizing water distribution networks (WDN), often ignoring the complexities of distribution systems due to their size and decision variables. Kang and Lansey (2012) propose a logical approach using genetic algorithms (GA) to optimize real-life, complex WDNs. They make several assumptions: demand is certain, the equations are approximate and uncertain, a single efficiency parameter represents pump performance, costs rely on a constant energy tariff, a single fire-flow pattern is used, and optimality cannot be mathematically proven for large WDNs. They aim to minimize WDN costs while ensuring reliability and meeting water pressure requirements. The study suggests an iterative approach:

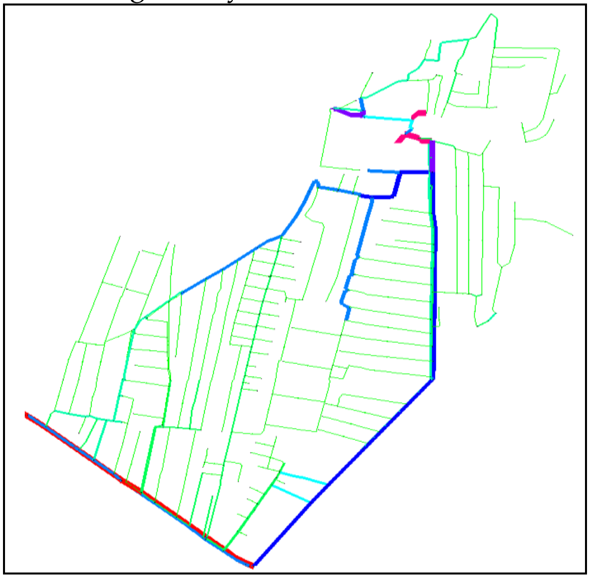
1. Start with minimum pipe sizes and conduct hydraulic simulations.
2. Compare computed flow velocities against a threshold.
3. Increase pipe diameter if velocities exceed limits and rerun simulations.
4. Repeat until all velocities are under the threshold, forming the initial population for GA.

This method addresses inconsistencies caused by random searches and emphasizes maintaining diversity in the initial population. The approach has shown benefits in a residential study network and can be applied to optimize transmission and distribution lines in practical WDNs.

III. CASE STUDY

This paper presents a Pimpri Chinchwad Municipal Corporation's (PCMC) WDN's district metered area (DMA) 'D-1' case study. M/s Dahasahasra Waternet Solutions, the consultant for PCMC, provided the hydraulic model data for this study. All the demands are residential. The demands range from 0.00 L/s to 3.23 L/s, and the total water demand in the DMA is 76.13 L/s. The hydraulic model was built on WaterGEMS SS4 v8i, and the junction demands were allocated spatially using a geographic information system (GIS). The network consists of one tank, 376 pipes, and 318 junctions subjected to base demands. The maximum and minimum values of pressures at the junctions are 24.516 meters of H2O and 5.476 meters of H2O, respectively. The pipes were laid considering the farthest demand from the tank to be covered, the terrain elevations, and the road network alignments. The network was designed for diameters based on head loss and velocity considerations to satisfy the allocated demands at adequate pressures. The model was considered for a steady state analysis for designing purposes. The cost of pipes for the consultant-designed model was Rupees 39,424,780.00. Figure 1 show the layout of the network, color-coded based on diameters:

Figure 1: Consultant-designed Hydraulic Model, Color-coded for Diameters



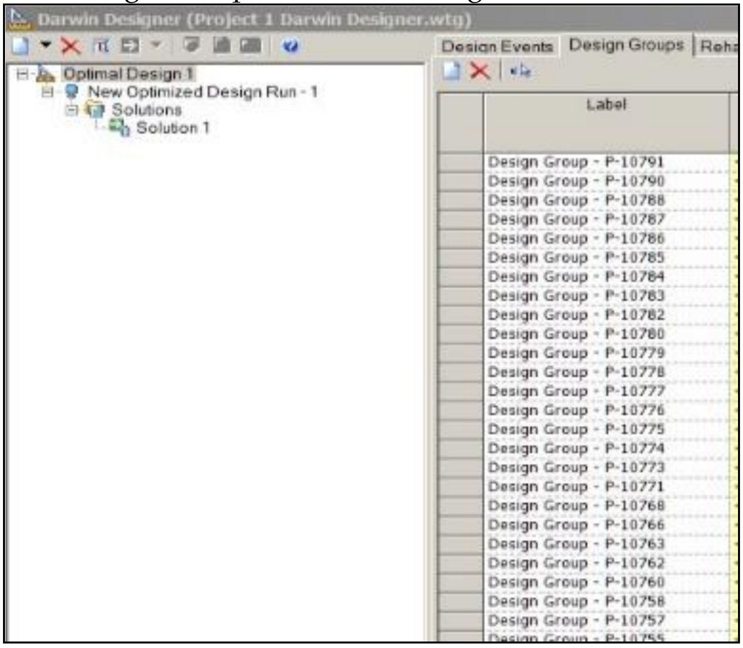
IV. THE PROBLEM

The main challenge in using Darwin Designer is the absurd optimal solutions it yields. These solutions are optimal, though, and follow all design constraints; however, they do not follow the logical 'telescopic pattern' as expected, given that the size would be reduced as the demand decreases. It is observed that the least cost constraint forces the Darwin Designer to consider larger pipe sizes at short lengths; this leads to a haphazard allocation of diameters to the pipes (Figure 2), as such pipe sizes are impractical.

Figure 2: Problem with Darwin Designer, Color-coded for Diameters

Darwin Designer enables users to create groups of pipes to determine their diameters. Each group is treated as a separate set of pipes, with all pipes in a specific design group sharing the same size. Typically, because every pipe must be designed, each one is viewed as its own design group, resulting in different optimal diameters for each pipe. Figure 3 shows the design groups for zone D-1 of the case study.

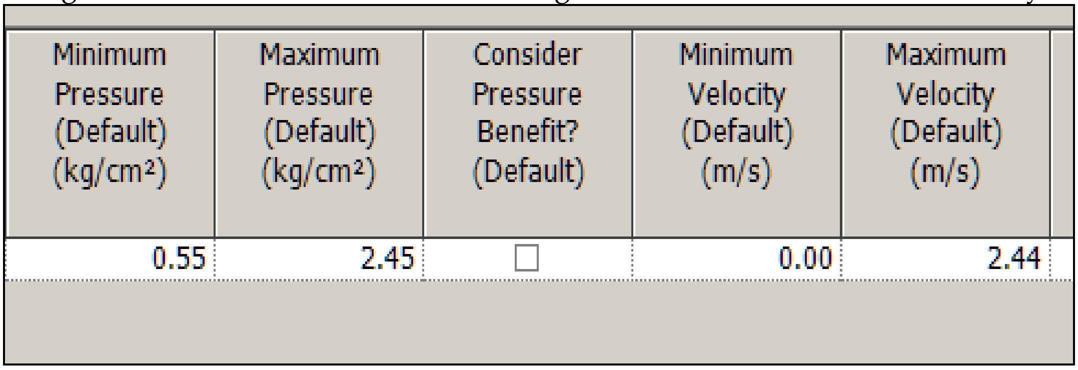
Figure 3: Design Groups in Darwin Designer, Conventional Setup



	Label
	Design Group - P-10791
	Design Group - P-10790
	Design Group - P-10788
	Design Group - P-10787
	Design Group - P-10786
	Design Group - P-10785
	Design Group - P-10784
	Design Group - P-10783
	Design Group - P-10782
	Design Group - P-10780
	Design Group - P-10779
	Design Group - P-10778
	Design Group - P-10777
	Design Group - P-10776
	Design Group - P-10775
	Design Group - P-10774
	Design Group - P-10773
	Design Group - P-10771
	Design Group - P-10768
	Design Group - P-10766
	Design Group - P-10763
	Design Group - P-10762
	Design Group - P-10760
	Design Group - P-10758
	Design Group - P-10757
	Design Group - P-10755

The number of design groups equals the number of pipes, thus considering every pipe as a separate design group. The minimum and maximum pressure constraints are set as 5.5 m of H2O and 24.5 m of H2O, respectively. The minimum and maximum velocity constraints are set as 0.0 m/s and 2.44 m/s, respectively.

Figure 4: Minimum and Maximum Design Constraints: Pressure and Velocity



Minimum Pressure (Default) (kg/cm²)	Maximum Pressure (Default) (kg/cm²)	Consider Pressure Benefit? (Default)	Minimum Velocity (Default) (m/s)	Maximum Velocity (Default) (m/s)
0.55	2.45	☐	0.00	2.44

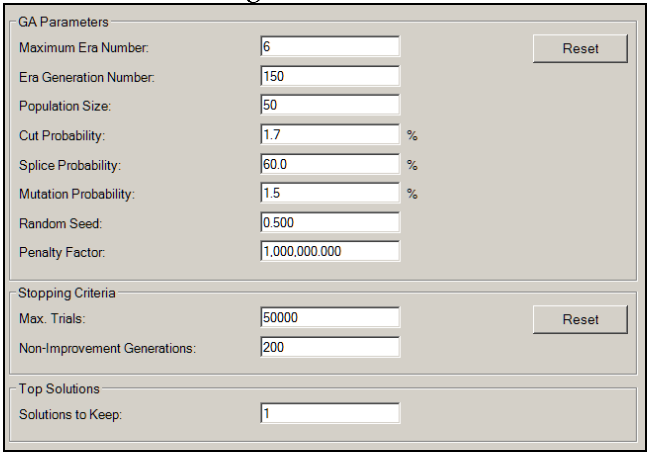
The material, diameter, Hazen-Williams C, and unit cost of pipes per meter length are shown in Table 1

Table 1: Pipe cost, Hazen-Williams C, Material, and Diameter for Design

Material	**Diameter (mm)**	**Hazen-Williams C**	**Cost $/meter**
Ductile Iron	25.4	130	2
Ductile Iron	50.8	130	5
Ductile Iron	76.2	130	8
Ductile Iron	101.6	130	11
Ductile Iron	152.4	130	16
Ductile Iron	203.2	130	23
Ductile Iron	254	130	32
Ductile Iron	304.8	130	50
Ductile Iron	355.6	130	60
Ductile Iron	406.4	130	90
Ductile Iron	457.2	130	130
Ductile Iron	508	130	170
Ductile Iron	558.8	130	300
Ductile Iron	609.6	130	550

Optimization aims to converge at the minimum cost design subject to a minimum pressure constraint of 5.5 m of H2O and a maximum velocity constraint of 1.8 m/s. The genetic algorithm parameters are set to default (Figure 5).

Figure 5: Default Genetic Algorithm Parameters in Darwin Designer



GA Parameters
Maximum Era Number: 6
Era Generation Number: 150
Population Size: 50
Cut Probability: 1.7 %
Splice Probability: 60.0 %
Mutation Probability: 1.5 %
Random Seed: 0.500
Penalty Factor: 1,000,000.000

Stopping Criteria
Max. Trials: 50000
Non-Improvement Generations: 200

Top Solutions
Solutions to Keep: 1

The optimal cost from Darwin Designer is Rs. 50,401,688.00, which is far greater than the cost of the existing network (Rs. 39,424,780.00). Even though the time taken was negligible, Darwin Designer designed each design group separately to satisfy the hydraulic constraints and achieve the global minima for the least cost function. This resulted in absurd diameters for the network. Figure 2 shows the network with optimal diameters resulting from Darwin Designer and is color-coded based on diameters.

It is observed that Darwin Designer offered an optimal solution but failed to realize the telescopic pattern in the network. It has given bigger diameters for smaller lengths to reduce the cost alone. Such designs would cause high head losses for peak demands or over a longer period as demands increase, and more minor losses would be induced because of sudden expansion and sudden contraction between the pipes. Such designs are useless even if the Genetic Algorithm behind the solver succeeds in achieving the optimal minimum cost.

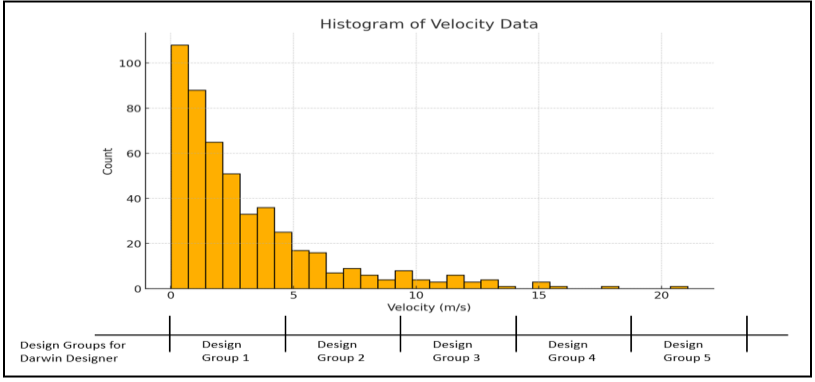
V. THE PROPOSED METHODOLOGY:

The hydraulic model is constructed with appropriate elevations, design demands, and boundary conditions. All pipes in the network are set to the least available size from the list of available pipe sizes for design. The model is computed with minimum size diameters.

Figure 6: Network Results, Minimum-size Pipes with Higher Flows and Velocities

Since the hydraulic modelling software is demand-driven, the model will analyze the network with minimum-size pipes and yield negative junction pressures and extremely high velocities. The pipes with the highest flows, i.e., the ones near the source (feeder mains), show the largest velocities. As the flow is dissipated in the network, the velocity reduces. Figure 8 illustrates a sample histogram of velocity distribution and the pipes' assignment to design groups. The pipe design groups in Darwin Designer are proposed to be created based on ranges in these velocities depending on their distribution.

Figure 7: Proposed Method - Design Groups in Darwin Designer



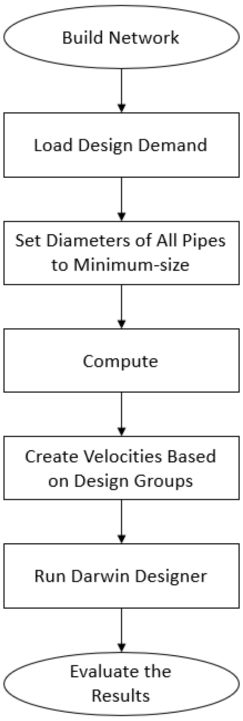
For the case study hydraulic model, a total of six design groups were created, which are shown in Table 2. Darwin Designer allows users to tweak the genetic algorithm optimization parameters. This is beyond the scope of this study.

Table 2: Design Group based on Velocity Distribution, Proposed Methodology

Design Group	**Velocity (m/s) Range**	**No. of Pipes**
Group 1	<= 1.8 m/s	211
Group 2	1.8m/s < X <= 2.5 m/s	99
Group 3	2.5 m/s < X <= 5 m/s	29
Group 4	5 m/s < X <= 13 m/s	24
Group 5	13 m/s < X <= 25 m/s	13
Group 6	> 25 m/s	5

A flowchart explaining the proposed methodology is shown in Figure 6.

Figure 8: Flowchart of the Proposed Methodology



VI. RESULT

The minimum cost-optimal solution with the proposed methodology was Rs. 32,066,794.00. The design did not violate any design constraint. The network post-design, color-coded for diameters, is shown in Figure 9.

Figure 9: Minimum Cost Design, Proposed Methodology

VII. CONCLUSION

The solutions search space was efficiently explored, reducing costs compared to the conventional method. Design inconsistencies were addressed, and the challenge of larger pipes downstream was effectively managed. Both feeder and distribution mains were designed with reasonable diameters, achieving a telescopic pattern. The proposed GA parameters successfully delivered cost-effective solutions without violating hydraulic constraints. Designing groups manually is time-consuming, but this methodology streamlines that process. The network's actual cost decreased from Rs. 39,424,780.00 to Rs. 32,066,794.00, significantly saving Rs. 7,357,986.00.

VIII. FUTURE RESEARCH

The discussed methodology can be applied to the design of rising and pumping mains, where optimal pipe sizing is crucial due to energy costs linked to flow and head. Flow rates depend significantly on pipe diameter, making balancing energy consumption and pipe costs essential, which can be explored using genetic algorithm parameters. There is potential for optimizing diameters in fire flow networks, where demands are pressure-dependent and high hydrant pressures are necessary. The Hazen-Williams Coefficient is important in hydraulic analysis; as pipes age, the C-value decreases, affecting network design and possibly necessitating updates to pipe cost properties. While this study aimed for the least cost solution, future research could optimize designs for minimal costs and maximum benefits, including improved pressures and fire flows.

International Journal of Core Engineering & Management
Volume-6, Issue-07, 2020 ISSN No: 2348-9510

REFERENCES

1. Andrade M. A., Kang D. Choi C. Y., Lansey K., (2013), "Heuristic Post Optimization Approaches for Design of Water Distribution Systems," American Society of Civil Engineers, Journal of Water Resources Planning And Management, Vol. 139, No. 4, 387-395.
2. Babu K. S. Jinesh, Vijayalakshmi D. P., (2013), "Self-Adaptive PSO-GA Hybrid Model for Combinatorial Water Distribution Network Design," American Society of Civil Engineers, Journal of Pipeline Systems Engineering And Practice, Vol. 4, No. 1, 57- 67.
3. Bentley Systems (2020) WaterGEMS, Bentley Systems, Exton, Pa.
4. Kadu M. S., Gupta R., Bhave P. R., (2007), "Optimal Design of Water Distribution Networks using a Modified Genetic Algorithm with Reduction in Search Space" American Society of Civil Engineers, Journal of Water Resources Planning And Management, Vol. 134, No. 2, 147-160.
5. Prasad T. Devi, Park Nam-Sik, (2004), "Multi-Objective Genetic Algorithm for Design of Water Distribution Networks," American Society of Civil Engineers, Journal of Water Resources Planning And Management, Vol. 130, No. 1, 73-82.
6. Savic D. A., Walters G. A., (1997), "Genetic Algorithm for Least Cost Design of Water Distribution Networks," American Society of Civil Engineers, Journal of Water Resources Planning And Management, Vol.123, No. 2, 73-82.
7. Vairavamoorthy K., Ali M., (2005), "Pipe Index Vector: A Method To Improve Genetic Algorithm-Based Pipe Optimization," American Society of Civil Engineers, Journal of Hydraulic Engineering, Vol. 131, No. 12, 1117-1125.
8. Wu Z., Walski T., (2005), "Self-Adaptive Penalty Approach Compared With Other Constraint-Handling Techniques For Pipeline Optimization," American Society of Civil Engineers, Journal of Water Resources Planning And Management Vol. 131, No. 3, 181-192.
9. Wu, Zheng et al., (2002, May 19-22), "Optimal Capacity Design of Water Distribution Systems," American Society of Civil Engineers' First Annual Environmental and Water Resources System Analysis (EWRSA) Symposium, Roanoke, VA.
10. Zheng F., A. R. Simpson, Zecchin A. C., (2011), "Dynamically Expanding Choice-Table Approach To Genetic Algorithm Optimization Of Water Distribution Systems," American Society of Civil Engineers, Journal of Water Resources Planning And Management Vol. 137, No. 6, 547-551.

ACKNOWLEDGEMENTS

The authors would like to thank M/s Dahasahasra Waternet Solutions for providing the data for this research.