The Optimatics Letter

Issue No. 1: July-September 1998 *Advances in Optimization for Water Distribution System Design & Operations*

A Primer on Optimization of Distribution Systems

Let's begin with a working definition of optimization. Optimization is simply the process of finding the best solution to a problem that may have many possible solutions.

Using this definition, it is evident there can be different methods for optimizing a given problem. For a simple problem, one could enumerate all possible solutions and then identify the best solution. Note that the best solution might not be the lowest cost solution, but some low-cost solution that has desirable non-quantifiable features as well.

Real-World Distribution Problems

Most planning, design and operations problems that water utilities face are too large and complex to solve by enumerating every possible solution. For a problem as simple as sizing 20 new distribution pipes given eight allowable pipe diameter choices, there are a total of 8^{20} or 1,152,921,504,606,850,000 possible combinations.

Now imagine that the designer must also consider minimum tank levels, refilling of tanks under maximum day demands, adequate tank drawdown to keep storage turning over, maintenance of chlorine residuals, blending of different water sources, and pump scheduling to minimize energy costs. With this level of complexity, it is clear a designer can use all the help he can get.

Formulating an Optimization Problem

Solving complex problems is what optimization analysis is all about. The first step for any optimization is to formulate the problem into an objective function and a set of constraints. The *objective function* defines the objective for the analysis: to minimize the cost of capital improvements or to minimize system operating costs over a given period, for example.

The *constraints* specify the conditions that any feasible solution to the problem must satisfy. The constraints might include minimum flow rates and pressures at all supply nodes for various demand cases (e.g., peak hour, maximum day, maximum day plus fire flow), minimum chlorine residuals over some extended period, and maximum supply rates from different water sources.

The constraints also specify the range of values that the problem's *decision variables* may take on. The decision variables might include pipe diameters, tank locations, pump selection, and the time at which pumps are turned on or off.

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Introduction to Issue No. 1

Water utilities today are facing a variety of new challenges and opportunities. These include more stringent water quality regulations, deregulated energy pricing, and new privatization options. To analyze the increasingly complex problems brought on by these changes, many utilities are turning to advanced analysis techniques to help them identify better solutions.

The Optimatics Letter is aimed at informing water utility managers and engineers, and their consultants, about the latest advances in optimization analysis techniques, focusing particularly on water distribution system optimization. We will report on how optimization is being used for system expansion and rehabilitation planning, improving system operations, and maintaining water quality. We will also monitor analysis advances that may help utilities in the future.

Our first issue reviews the basics of distribution system optimization. The optimization approach is contrasted with current practice based on simulation analysis alone. A case study of an expansion planning optimization for a Colorado water district is presented.

The Future of Computing

According to a June 14, 1998 National Public Radio story, the Defense Advanced Research Projects Agency (DARPA) is looking outside the domain of silicone chip-based digital computers to entirely new computer forms for the next great leap forward in computing power.

DARPA's latest research is in *quantum computing,* which uses molecules, atoms and even particles of light as the computer's central processing unit. While digital computers are based on two distinct states—yes/no, 1/0, on/off, true/false—quantum systems can simultaneously be in two states at once. If this weird property can be harnessed so that each individual atom can compute, then one cubic centimeter of salt would represent more computing power than all the computers in the world right now.

DNA Computing

Another concept is computers based on DNA molecules. Life's building blocks, DNA molecules are really digital information recording systems. One could brew up a liquid of short DNA strings representing all possible solutions to a problem, such as finding the best route for a traveling salesman. Enzymes could then fish out the optimal solution from the hundreds of trillions of combinations in the liquid. This methodology is similar to genetic algorithm optimization, except that the GA searches through numeric strings rather than physical DNA molecules.

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Finally, the optimization formulation will specify other relevant *parameters*. These could include the installed cost of pipes and pumps, energy costs according to a prevailing rate schedule, and pipe roughness coefficients for different pipe materials and sizes.

Once the problem is formulated, the analysis proceeds to identify an optimal solution or several near-optimal solutions. The optimal solution is simply that mix of decision variable values that results in the optimal value (usually minimum cost) of the objective function.

Applying Optimization—It's Not Easy

Since the 1960s, various optimization techniques have been tested on water distribution system design and operations problems. Formal mathematical methods like linear programming, dynamic programming, non-linear programming, partial enumeration and gradient search have been applied but have met with only limited success.

The reasons for the limited success of these standard techniques has to do both with the complex nature of distribution system problems and the inherent limitations of the optimization methods themselves. For example, depending on which technique is being used, the problem must be formulated using only linear functions or differentiable functions, or at least continuous functions.

Sizing pipes in a branching system (no loops) fed from a single source is one class of problem that can be formulated and solved using the standard techniques mentioned above. Another level of complexity, however, is added when looped distribution systems are analyzed. This is because flows through a looped system depend not only on the system demands and layout, but also on the pipe diameters chosen and the operation of pumps and valves. Many of the standard optimization techniques cannot handle real-world looped systems.

Much of the recent work on optimization of distribution system problems has moved away from standard mathematical formulations to approaches based on guided search. The new methods often combine an optimization routine with a hydraulic network solver. The basic approach is to generate one trial solution (or a large set of trial solutions) and then to evaluate the solution(s) using the network solver. The optimization automatically searches for better and better solutions as successive trial solutions are generated and

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Optimal pipe locations are determined by including a zero pipe size as an allowable choice; the optimization will select a zero size for all non-optimal pipe locations.

Sensitivity analyses are performed by varying the values of different parameters over a series of optimization runs.

Distribution Optimization Applications

Optimization analysis can be effectively applied to a variety of distribution problems. It can be used in *planning* a distribution system to determine the layout of pipes, tanks, pumps, valves and treatment facilities. It can also be used to optimize the timing of these facilities improvements in a capital improvement program. Optimization can be applied during *design* to help finalize the best mix of sizes and settings for the facilities.

For an existing system, optimization analysis can be used to identify improved operating policies or to optimize real-time operation. Improving *operating policies* would involve optimizing the timing and settings for valves and pumps for various design conditions, such as peak hour, maximum day or average day.

Optimizing *real-time operations* is a similar type of analysis, but in this case predicted conditions rather than design conditions are used. Data on current (and prior) water levels, pressures and settings, as well as predicted demand data are required as input to the optimization. A short-term forecasting model based on historical records, weather forecasts, etc. can provide demand data for several time steps into the future. An optimization analysis is then run for each time step using the latest data to update operational plans. The updated actions can be implemented directly via SCADA control.

Case Study #1: FCLWD Expansion

Fort Collins-Loveland Water District in Colorado desired a system expansion plan to meet year 2015 demand conditions for its 60 square mile service area. A consultant developed the plan using an EPANET model having 5 pressure zones, 7 reservoirs, 3 pump stations, 14 pressure reducing valves (PRVs) and 3 interconnects to adjacent systems. The recommended solution called for 46 new pipes totaling 29.4 miles in length.

Recognizing that other layouts might be more cost effective, FCLWD decided to evaluate the plan using GA optimization analysis. The EPANET model data were read into Optimatics proprietary OGA optimization program. Allowable choices for pipe locations, pipe diameters and PRV settings, along with corresponding installed costs, were also input.

The OGA optimization then searched for the combination of pipe sizes and PRV settings that would minimize the capital cost of improvements while meeting all hydraulic design criteria and supplying 2015 demands. The optimized solution had just 22 new pipes totaling 18.8 miles. The estimated capital cost for the system expansion dropped from $5,850,000 to $2,970,000, a cost savings of 49%. *(See system layout on back page.)*

FCLWD **Systems Engineer Terry Farrill** said at first he did not believe the optimized solution would actually supply the required demands. After he tested the GA solution himself in the original EPANET model, he was satisfied it was a viable alternative that met the required design criteria. The optimized expansion solution was then made the basis for the District's new CIP.

tested. This approach, as represented by genetic algorithm optimization, has shown good success for a wide range of distribution applications.

Optimization Can Build on Simulation

Given this general background, let's now consider how optimization analysis compares with current distribution system analysis practice. Current practice is based on the system being modeled using a hydraulic simulation program, such as Cybernet, EPANET, H_2ONET, KYPIPE, or Stoner SWS. Assuming the model is accurately calibrated, network analysis can be used to identify the causes of deficiencies in the system and to develop improvements.

AWWA Manual M32, *Distribution Network Analysis for Water Utilities,* describes the standard analysis procedures for steady-state model simulations. System deficiencies are determined by comparing the model-predicted performance to established design and operational standards. Deficiencies in the system are generally indicated by inadequate system pressures.

When deficiencies are identified for existing or projected future demand conditions, the designer or modeler formulates and tests a trial solution in the model. Revisions to piping, pumping, storage and system operations are made, and the model is re-run to test the new solution. This trial-and-error process is repeated until the deficiencies are corrected.

As Manual M32 puts it, "System analysis is partly a science and partly an interactive trial-and-error art that incorporates the feel of the distribution system." The weakness of the simulation approach then is that it relies solely on a human designer to locate and size improvements and revise operational settings. Given the tremendous complexity of real-world distribution problems, relying on a designer's "feel" will rarely achieve the best possible results.

In contrast, optimization analysis permits the designer to supplement his judgment with the power of the computer to identify near-optimal solution alternatives. In addition, by using optimization methods that combine with hydraulic network solvers, such as genetic algorithms, the designer can incorporate the sophisticated capabilities of the simulation program into the optimization analysis.

A Summary of Optimization Benefits

Optimization represents the logical next step in distribution system analysis once a hydraulic simulation model is prepared. The latest optimization techniques combine well with today's simulation programs to take advantage of their advanced hydraulic and water quality modeling capabilities. The optimization then can be applied to any type of problem the simulation model is set up to handle, including planning, design and system operations applications.

Optimization analysis allows designers to investigate hundreds of thousands of trial solutions to find viable, cost-effective alternatives. Optimization can often achieve significant capital and operating cost savings compared to solutions found using simulation analysis alone.

Finally, any interesting solutions identified by the optimization can be evaluated in the same manner as the trial solutions developed by a designer. The optimized solutions can be verified simply by running them in the original simulation model to confirm that all specified design criteria are satisfied.

Calendar of Events

August 16-19 [1]
Georgia AWWA Section Conference in Atlanta

September 20-23
AWWA Distribution System Symposium in Austin, TX

September 22 [2]
OGA Optimization Seminar hosted by Manatee County Public Works, Bradenton, FL

October 5 [2]
OGA Optimization Seminar hosted by Carollo Engineers in Sacramento, CA

October 6-9 [1]
Cal-Nev AWWA Section Conference in Reno, NV

November 8-11 [1]
Florida AWWA Section Conference in Orlando

[1] FWE staff will exhibit and/or present a technical paper.
[2] FWE staff to lead the seminar.

The EPA's January 1997 Drinking Water Infrastructure Needs Survey *estimates an $89.3 billion need for storage, transmission and distribution over the next 20 years.*

If this amount could be reduced by just 10% through the use of the latest optimization techniques, cost savings would be significant for many water utilities.

The Optimatics Letter

Advances in optimization for water utilities and consultants

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Please pass this newsletter on to key staff involved in distribution system planning and operations.

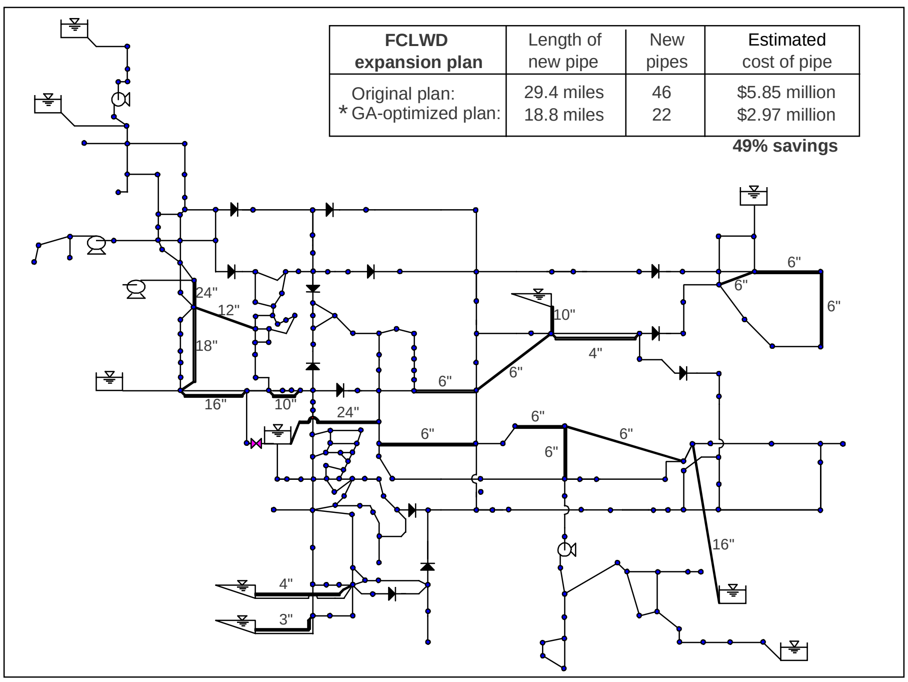
Also, please call or e-mail us to update names and addresses or to add new names to the mailing list.

The Optimatics Letter

Advances in Optimization for Water Distribution System Design & Operations

In this issue, you can read about:

- What optimization is and how it is being applied to water distribution system problems.
- How Fort Collins-Loveland Water District is **saving nearly $3 million** in capital improvement costs.
- Why current simulation analysis practice fails to identify the most cost-effective solutions.
- How optimization builds on today's sophisticated simulation programs for a variety of applications.



FCLWD expansion plan	Length of new pipe	New pipes	Estimated cost of pipe
Original plan:	29.4 miles	46	$5.85 million
* GA-optimized plan:	18.8 miles	22	$2.97 million
			49% savings