OPTIMIZING WATER SYSTEM IMPROVEMENT FOR A GROWING COMMUNITY

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Abstract

To meet the water supply requirement in a growing community, system improvement alternatives needs to be identified to satisfy the increasing demand. This paper shows that the intelligent optimization modeling tool can assist practical engineers and decision-maker to optimize system expansions and prioritize the budget allocation of capital improvement program (CIP) for a real world water system. The water distribution system undertaken for study represents a community where the water consumption is projected to grow 30% in 15 years. Increasing consumption requires that the water system be improved to move water from sources into the growing areas. The criteria for enhancing the system capacity include satisfying the pressure requirement, the maximum allowable flow velocity and sufficient tank storage. The improvement task is to identify the feasible pipe routes and pipe sizes of the new pipes. Due to the complex interconnectivity and the large combinations of possible pipe routes/sizes, it proved technically difficult for experienced engineers to identify a feasible design solution. GA-based optimization design tool has been applied to forge the cost-effective system improvement solutions. The study shows that optimization modeling is a powerful approach for supporting and enhancing a sound decision-making process in water industry.

Keywords
Water supply, model, optimization, optimal design

1. INTRODUCTION

America Society of Civil Engineers (ASCE) has conducted annual survey on the national infrastructure systems. The latest survey reports (ASCE 2005) that the nation's 54,000 drinking water systems face staggering investment needs over the next 20 years. Although America spends billions on infrastructure each year, drinking water faces an annual shortfall of at least $11 billion to replace aging facilities that are near the end of their useful life and to comply with existing and future federal water regulations. Federal funding for drinking water in 2005 remained level at $850 million, less than 10% of total national requirement. The shortfall does not account for any growth in the demand for drinking water over the next 20 years. To meet the demand in a growing community and to improve the aged water infrastructures, system improvement alternatives must be optimized to deliver the maximum return for every dollar spent. This study illustrates a typical example of real world water systems that the intelligent optimization modeling tool can assist practical engineers and decision-maker to optimize system expansions and prioritize the budget allocation of capital improvement program (CIP).

2. OPTIMAL DESIGN IN A NUT SHELL

Applying a genetic algorithm to optimizing water distribution systems has been well studied over last decade (Simpson et al. 1994; Savic & Walters 1997; Wu & Simpson 2001; Wu et al. 2001; 2002 and many others). There are three types of optimization models including least cost design, maximum benefit design, and cost-benefit tradeoff design. Least cost optimization searches for the optimal solution by minimizing the cost while satisfying the design constraints. The least cost optimization, however, produces the minimum pipe sizes which reduce the supply capacity and reliability. The goal for water utilities to design a water system is to maximize the return on every dollar spent. Maximum benefit design optimization can assist engineers to achieve this goal by searching for the maximum benefit design solution within an available budget while still meeting hydraulic constraints. Both the least cost and the maximum benefit optimization models identify the optimal or near-optimal solutions at the minimum cost and the maximum benefit (often corresponding to the maximum cost) respectively. The solutions in between two extreme costs are unlikely to be identified for cost-benefit tradeoff analysis by a single objective design model. Using a multi-objective genetic algorithm, Wu et al. (2002) and Walski et al. (2003) demonstrate that the cost-benefit tradeoff optimization is able to identify the sound solutions at every cost levels within a budget by simultaneously minimizing the cost and maximizing the benefit while satisfying the constraints.

With carefully defined design objectives and design constraints, water distribution optimization models of the least cost design, maximum benefit design, and cost-benefit tradeoff design are generalized as a constrained nonlinear programming problem, that is to search for the optimal design solution $\vec{X}$ (design variables), subject to a set of nonlinear constraints, given as:

search for: $\vec{X} = (x_1, x_2, ..., x_n) \in \boldsymbol{R}^n$ (1)

minimize Cost: $C(\vec{X})$ and/or (2)

maximize Benefit: $B(\vec{X})$ (3)

subject to: $g_j(\vec{X}) \geq 0 \quad j = 1, 2, ..., M;$ (4)

$x_i \in X_i^0 \quad i = 1, 2, ..., N;$ (5)

Where R^n is the solution space of design variable $\vec{X}$, $g_j(\vec{X})$ is the constraint function that defines the feasible region of the search space, X_i^0 is the set of possible values (e.g. possible pipe sizes) for optimization variable x_i. The optimal design formulated above is solved within a framework of fast messy genetic algorithm (fmGA) (Goldberg et al. 1993). The fmGA is embedded into optimal design tool Darwin Designer (Haestad 2003) that is applied to the optimization design modeling in this study.

3. OPTIMIZATION STUDY

The water distribution system undertaken for study is currently supplying about 18.3 million gallon of water for a peak day demand (the real name of the water system is not explicitly mentioned due to the security concerns). The hydraulic model has been constructed and calibrated to represent the system hydraulic conditions on a typical summer day. It also served as an analysis model for system optimization. The hydraulic network model, as shown in Figure 1, contains 2018 pipes, 1371 nodes, 3 pumps, 1 reservoir, 9 elevated storage tanks and 20 wells.

Water is directly pumped into the system. A total of 18.27 million gallons is produced from all water sources each day, including 14.45 million gallons from the wells and about 3.83 million gallons from reservoir. During low demand period (from 10:00 P.M. to 4:00 A.M.) extra water supplied by the sources is stored in tanks for high demand period. Daily system demand is about 18.06 million gallons.

Water consumption is projected to grow 30% in the service areas around tank T-1, which are becoming popular for living and thus represent a growing community. Increasing consumption results in a total daily system demand of 24.2 million gallons in 15 years.

3.1 Improvement Criteria

To meet the increasing demand, more water needs to be moved from the water sources into the growing areas. Following criteria are postulated for enhancing the system capacity.

1. Satisfy the minimum required junction pressure of 30.0 psi and the maximum allowable pressure of 100.0 psi.
2. Satisfy the maximum flow velocity of 6 feet per second (fps) for distribution pipes and 10 fps for transmission mains.
3. Refill all of the tanks, particularly elevated tank T-1.

Therefore, the improvement task is to identify where to lay new pipes and what sizes the new pipes are. New pipes are mostly laid in parallel to existing pipes to deliver water from the sources into the distribution system. Due to the complex interconnectivity and the large combinations of possible pipe routes/sizes (26 possible pipes are identified, each pipe can be sized as one of 7 possible sizes, a total of 7^{26}, about 9×10^{21} potential solutions exist.), it is proven technically difficult for experienced engineers to identify a feasible design solution. The fmGA-based design tool is employed to conduct the optimization modeling for finding the system improvement solution.

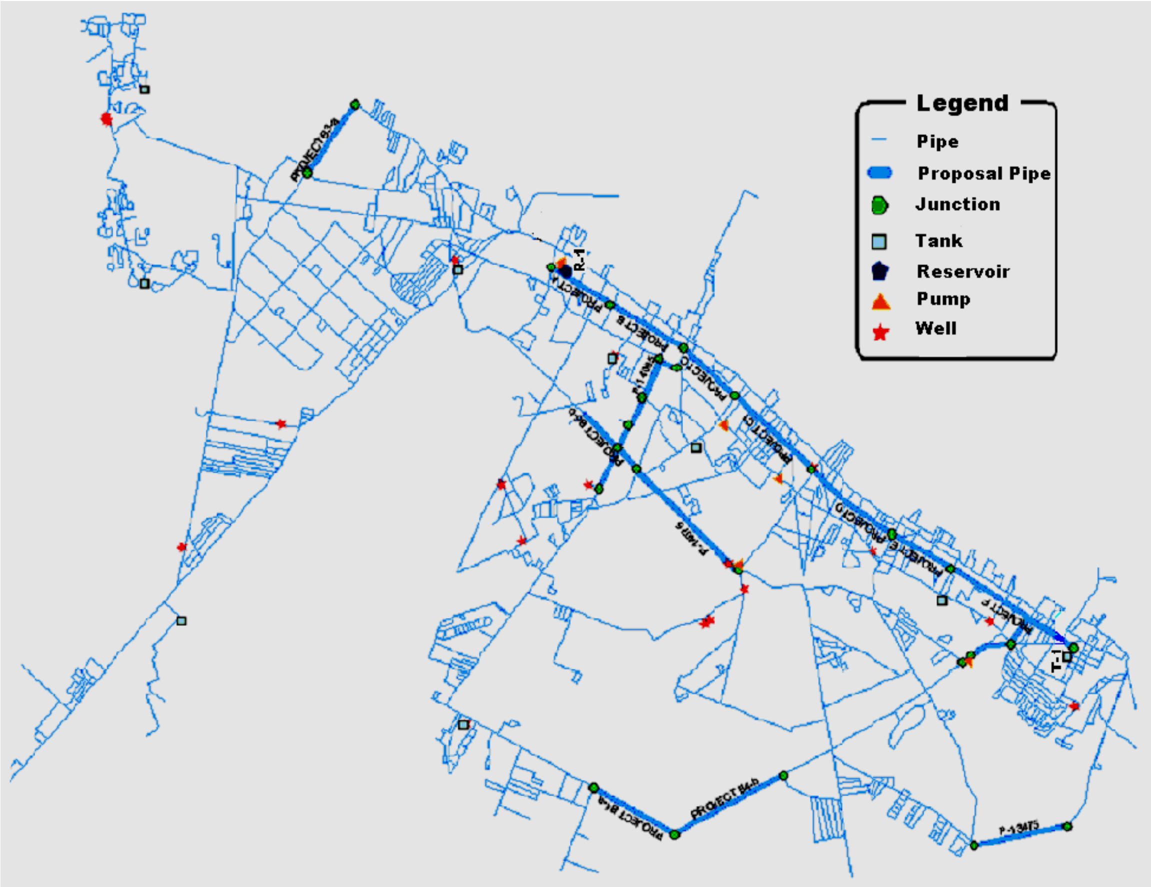

Figure 1 Layout of water system undertaken for optimization design study

3.2 Optimization Model

Optimization model has been constructed by using Darwin Designer, an integrated optimization modeling tool for efficiently evaluating design solutions. The tool allows modelers to set up the multiple design criteria and conduct optimization design runs for different loading conditions, boundary settings (tank level, pump/pipe status and valve setting), design pipe groups and hydraulic constraints, as shown in Figure 2.

In this model, available pipe sizes are 0, 6, 8, 12, 16, 20 and 24 inch for all twenty-six (26) pipes. A zero size is to represent the option that there is no need to lay a new pipe. To ensure that the tank is refilling, a minimum flow velocity constraint is specified for the pipe connected to the tank. It enforces the inflow to the tank during the filling period Optimization study has been carried out for different operating conditions and development alternatives.

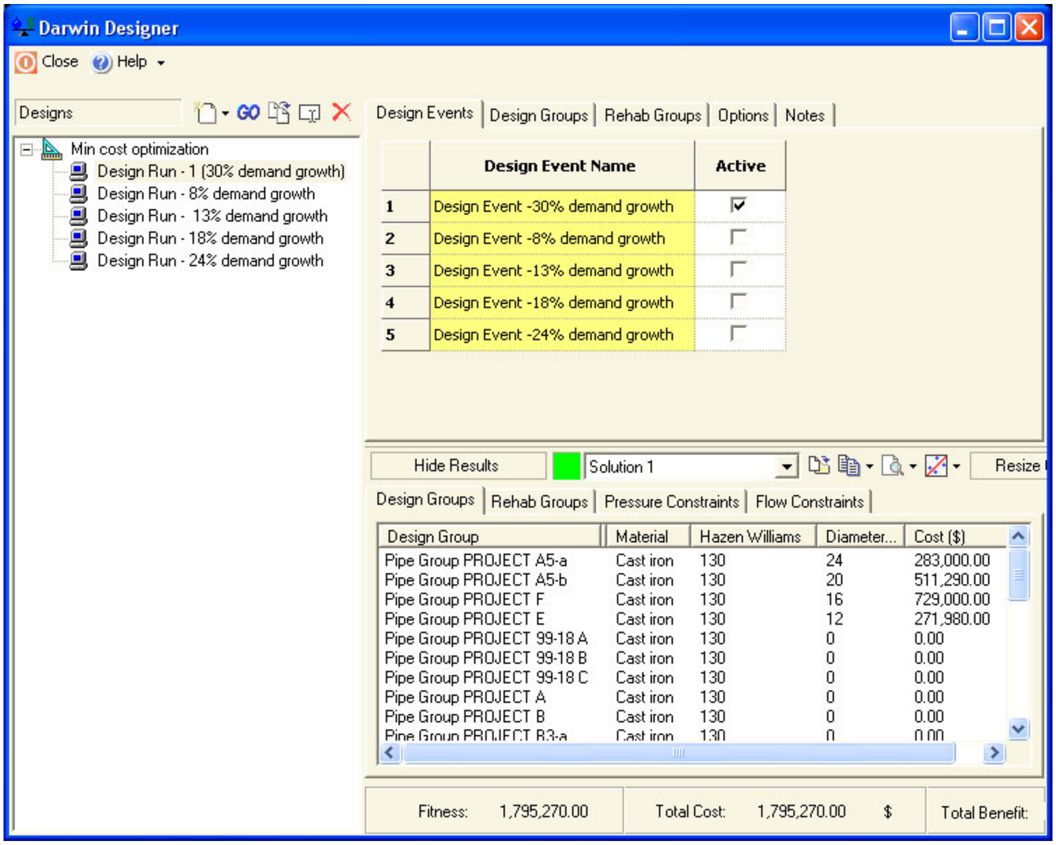

Figure 2 Exemplification of Darwin design optimization model

3.3 Optimization Modeling Results

The optimization runs have been performed for optimizing improvement solutions for the following scenarios:

1. Satisfying full demand growth;
2. Determining sustainable demand growth;
3. Maximizing water production and;
4. Prioritizing phase-in capital improvement.

3.3.1 Full Demand Growth

Optimization modeling has first been conducted with the originally full demand growth (30% increase of the existing consumption). Multiple optimal solutions are retained for verifying the tank level by exporting the solutions from design optimization module to hydraulic model. The optimal solutions are evaluated by extended period simulation (EPS) to ensure a cyclic tank operation.

It was found that only one solution can refill the tank to 100% full for the first day, but after each subsequent day the initial tank level drops lower and lower. It seems to stabilize between 30% and 60% full. This indicates that, due to the high demand and lack of supply, the tank can not be refilled to an adequate level for the next supply cycle; stored water within the tank is used to supplement the water that is produced, resulting in a net decrease in storage as time passes. The optimization results suggest that either the future demand is too high or that the available water sources cannot meet the demands. Therefore, it is imperative to find out the maximum sustainable demand growth under currently water source capacity.

3.3.2 Sustainable Demand Growth

With design optimization model, the sustainable demand growth can be easily identified, along with the optimal solutions for satisfying the demand. Using the same design criteria and constraints, optimization runs are modified and performed with different demand growth rates. The optimal solution with 5% demand growth reduction is found to be able to refill the tank to an adequate level. This equates to about one million gallon per day being deducted from the originally projected full demand growth. Consequently, it indicates that the maximum sustainable supply is 25% demand growth under current water production.

To meet the originally planned 30% demand growth, water production capacity needs to be maximized for both the reservoir and the wells; corresponding optimal system improvement can then be located.

3.3.3 Maximizing Water Production

It is due to the shortage of water supply from the available sources that a stable operating cycle cannot be established at tank T-1. This analysis assumes that unlimited water is available from the reservoir. All of the previously optimized solutions are simulated for a long period of supply, it is demonstrated that all of the solutions can refill and establish a stable cyclic tank operation. However, it requires for 5.82 mgd being supplied from the reservoir, which is out of the reservoir production capacity.

Alternatively, extra water can be supplied from 20 wells throughout the system. Three wells are found not supplying water during tank filling hours under present operation arrangement. Thus, the optimization model has been rerun with the maximum well supply capacity (three wells turned on). The optimal solution with an estimated cost of $2.96 million is obtained and verified that it satisfies all of the constraints and establishes a good tank operating cycle.

3.3.4 Optimal Phase-in Improvement

Phase-in improvement is to prioritize the construction of the new design pipes, or how to schedule the capital improvement program to enhance the system capacity, in other words, which pipe and what size should be installed first in order to meet the growing demand. This is an important decision for budget allocation over a planning horizon.

To conduct Phase-in design optimization, the optimal design model is modified with five demand loadings including:

- 8% demand growth, corresponding to 20.06 mgd base demand for the system;
- 13% demand growth, corresponding to 21.00 mgd base demand for the system;
- 18% demand growth, corresponding to 21.90 mgd base demand for the system;
- 24% demand growth, corresponding to 23.03 mgd base demand for the system;
- 30% demand growth, corresponding to 24.22 mgd base demand for the system;

The other design criteria and constraints are the same as the optimization runs carried out earlier.

Optimal solutions obtained for all five phase-in demand growth are summarized in Table 1. It clearly indicates the priority of new pipe installation. The optimization runs have been conducted separately for each of demand-growth loading conditions, instead of incrementally from an initial phase. Although the optimal pipe sizes are different from the initial phase (8% demand growth) when compared to later phases (a smaller pipe is the optimal solution for the initial demand growth, but no extra capacity will be available to meet the later demand growth), the priority of the new pipes is clearly identified as demand increases from 8% to 30% of the existing demand. To meet 8% to 18% demand growth, Pipes PROJECT A and PROJECT B are the most critical improvement pipes. To meet a greater demand growth, pipes PROJECT F and PROJECT E must be installed. Finally, the construction of PROJECT D needs to be undertaken for delivering adequate supply of full demand growth in fifteen (15) years.

4. FINAL REMARKS

The optimization modeling carried out in this study successfully optimized the improvement solutions for various system conditions of demand growth, water source options and phase-in development. Multiple top solutions are retained for further analysis of sustainable supply over extended period simulation. It helps engineers to better understand the hydraulic and water quality impact of the expansion, hence facilitates the decision process to protect the stakeholders' investment in water asset and also satisfy the customer's expectation. Optimization modeling is proven a powerful approach for supporting a sound decision-making process of determining cost-effective improvement alternatives. It allows modelers to quickly set up a model, emulate the governing decision criteria and conduct evaluation of a large number of possible solutions.

Finally, an optimization model encapsulates the valuable knowledge of system characteristics and intelligent computing technology. It is the knowledge-rich tool that transfers knowledge to modelers. When an optimization study is carried out using the optimization modeling tool in hand, not only can the system be optimized and the design solutions provided, but also an optimization model is constructed, water utilities own the model along with hydraulic model. The optimization model is not only the valuable investment for water utilities but also encapsulates their system design expertise and also important information of design rules, constraints and criteria etc. that can be modified at user's convenience and thus the optimization model can be reused for future needs.

Table 1 Optimal Solutions with Phase-in Demand Growth

	8% Growth (20.06 mgd)		13% Growth (21.00 mgd)		18% Growth (21.92 mgd)		24% Growth (23.03 mgd)		30.4% Growth (24.22 mgd)	
Pipe ID	Diam (inch)	Cost ($)	Diam (inch)	Cost ($)	Diam (inch)	Cost ($)	Diam (inch)	Cost ($)	Diam (inch)	Cost ($)
P-2210	0	0	0	0	0	0	0	0	0	0
P-15	0	0	0	0	0	0	0	0	0	0
P-16	0	0	0	0	0	0	0	0	0	0
P-13475	0	0	0	0	0	0	0	0	0	0
PROJECT B4-a	0	0	0	0	0	0	0	0	0	0
PROJECT B3-a	0	0	0	0	0	0	0	0	0	0
PROJECT B3-b	0	0	0	0	0	0	0	0	0	0
PROJECT B4-b	0	0	0	0	0	0	0	0	0	0
PROJECT B7-a	0	0	0	0	0	0	0	0	0	0
PROJECT B7-c	0	0	0	0	0	0	0	0	0	0
PROJECT B7-b	0	0	0	0	0	0	0	0	0	0
PROJECT B6-a	0	0	0	0	0	0	0	0	0	0
PROJECT B6-b	0	0	0	0	0	0	0	0	0	0
PROJECT A5-a	12	169,800	16	212,250	16	212,250	16	212,250	24	283,000
PROJECT A5-b	20	511,290	20	511,290	24	568,100	16	426,075	24	568,100
PROJECT A	0	0	0	0	0	0	0	0	0	0
PROJECT B	0	0	0	0	0	0	0	0	0	0
PROJECT C	0	0	0	0	0	0	0	0	0	0
PROJECT E	0	0	0	0	0	0	16	339,975	24	453,300
PROJECT F	0	0	0	0	0	0	20	874,800	24	972,000
PROJECT C1	0	0	0	0	0	0	0	0	0	0
PROJECT D	0	0	0	0	0	0	0	0	24	681,900
P-14090	0	0	0	0	0	0	0	0	0	0
P-14075	0	0	0	0	0	0	0	0	0	0
P-14080	0	0	0	0	0	0	0	0	0	0
P-14085	0	0	0	0	0	0	0	0	0	0
Total Cost ($)	681,090		723,540		780,350		1,853,100		2,958,300	

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