Multiobjective Optimization in the Operation of a Water Distribution System Using the Elitist Evolutionary Algorithm(SPEA): a Case Study from Brazil

I.B.Carrijo
Goiás State Sanitation Company-SANEAGO, Goiânia, Brazil

L.F.R.Reis
São Carlos School of Engineering-USP, São Carlos, Brazil

G.A. Walters
Centre for Water Systems, University of Exeter

D. Savic
Centre for Water Systems, University of Exeter

Abstract

The efficient operation of a system is a fundamental tool for extending the system's service life as much as possible and ensuring good service to the consumer. This is in addition to keeping electrical energy and maintenance costs at acceptable levels. Efficient operation requires detailed knowledge of the system and this knowledge provides two benefits. First, supported by tools such as models for hydraulic simulation and operational optimization, it provides the operator with proper conditions for the rational operation of the system. Second, it maintains the system's reliability, without depending exclusively on the personal experience of the system manager. This paper introduces a computational model for the optimal operational control of macro water distribution systems using the EPANET2 hydraulic simulator. Recognizing the multi-objective nature of the optimal operation problems of water distribution systems, this study shows an application of an elitist multi-objective evolutionary algorithm, namely the Strength Pareto Evolutionary Algorithm (SPEA), to generate a series of non-dominated solutions. The optimal operation analyses were conducted on the macro water system of the city of Goiânia in Brazil. This was in order to minimize the cost of the electrical energy in the pump stations and to maximize the hydraulic benefits in terms of the required pressure at the demand nodes and of adequate reservoir levels. The results quantify the benefits to the system and provide a set of optimal solutions for satisfactory operation of the water distribution system.

Keywords: multiobjective optimization, genetic algorithms, optimal operation.

1. INTRODUCTION

The concept of systems operation, understood by laypersons as a mere sequence of equipment commands whose objective is to meet the demand [1], is actually far more complex, involving aspects of planning, control and supervision, and infrastructural consumer support and services, all of which are considered simultaneous and interdependent.

The operation plan requires that at least four basic conditions be met: a) a clear definition of the objectives to be achieved; b) the availability of mathematical analysis models; c) equipment to process these models; and d) knowledge of the system [2].

The medium and large systems are designed and operated based on global efficiency, involving issues such as reliability, pressure and demand distribution, energy consumption, minimization of losses, etc [3]. In this global approach, questions of numerical efficiency are associated with providing answers about complex operational issues, driving researchers to develop appropriate numerical techniques that allow for the solution of highly complex specific or general problems.

Optimization techniques have traditionally been used to design water distribution system units at low cost. According to [3], the interface between the hydraulic simulation model and the optimization model should be carefully built to give the model transparency, thereby facilitating its use, and allowing for the analysis of complex problems involving multiple objectives. Algorithms based on a stochastic search process have been used successfully because they are easy to use and their applications are practically unlimited. This is an optimization model that allows for the introduction of heuristic rules. A GA is a search algorithm based on natural selection and on the genetics of populational evolution. Its advantage over other techniques is that, by directly analyzing a population of feasible solutions through the improvement of successive populations, high performance solutions are found in terms of the multiobjective criteria defined by the problem.

The purpose of this work is to present a methodology to achieve the optimal operation of water distribution systems, essentially macro systems (skeleton), concerning the costs of the operation (electrical energy) and the hydraulic benefits. It represents an attempt to provide a set of adequate operation rules in order to minimize costs and maximize hydraulic benefits. Based on the knowledge of the system, the purpose is to optimize its operation through multiobjective genetic algorithms (MOGAs), supported by a realistic hydraulic simulation model of the system behavior.

2. METHODOLOGY

The purpose of operating water supply systems is, at acceptable risks, to meet the needs of consumption and minimize operational costs and, implicitly, to take the best possible advantage of the transport and reservoir system so as to retard expansion-related investments. The system's operation is a sequence of actions taken on the active elements of the system, such as valves and pumps in order to meet the objectives.

The optimization implemented here takes into account two objectives: the minimization of the operational costs and the maximization of the hydraulic benefits, considering the index of demand met, adequate levels of water in the tanks, and minimum and maximum pressures at the demand points for a 24-hour period of analysis.

2.1 Hydraulic Simulation of the System

The hydraulic simulation evaluates the system's response to operational decisions in terms of their variables of state, i.e., pressure, flow rate and level in the tanks. It is therefore an essential tool for the computational routine which quantifies the established objectives. EPANET2, via Toolkit [4], is used for this purpose.

2.1 Operational Optimization Using Multiobjective Genetic Algorithms

Optimization techniques are used to search for optimal solutions for a specific operational problem. If the objective is, for instance, to minimize the operational cost, the cost function will be associated with the price of electrical energy, pump discharge, load losses at the facilities, etc [2]. On the other hand, to meet the objective of minimum cost, the system itself imposes restrictions, such as maximum and minimum tank levels, limits of pressure and of power and quantity of available water.

The use of optimization techniques to solve control problems poses some difficulties, involving the large number of equations to be solved, formulation of the general problem, treatment of inexplicit operational restrictions, and data acquisition and maintenance.

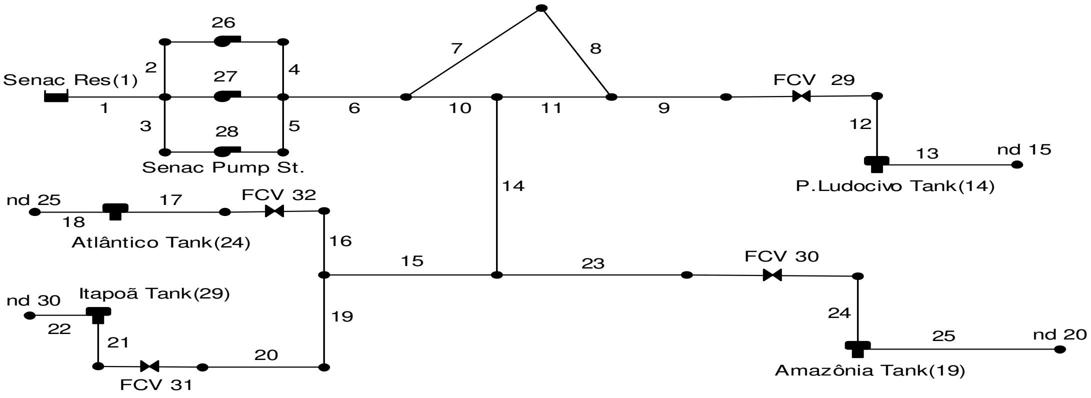
The goal of the multiobjective GA is to find the optimal Pareto set (also called optimal Pareto boundary), which corresponds to the set of all the non-dominant solutions of the search space [5]. GAs are naturally appropriate for the analysis of the Pareto surface because they work with populations of solutions, yielding as answers a set of optimal solutions rather than a single solution.

According [5] and [6], since 1993, different evolutionary algorithms have been proposed for the solution of multiobjective optimization problems. *The Multi-Objective Genetic Algorithm*

(MOGA), the Niched-Pareto Genetic Algorithm (NPGA), and *the Non-dominated Sorting Genetic Algorithm (NSGA)*, were the precursors of this technique, whose basic characteristics are: evaluation of the members of a population based on the Pareto dominance concept and on preservation of the diversity of solutions. Although these algorithms have proven efficient to obtain multiple non-dominant solutions to various engineering problems, researchers have suggested the introduction of elitism to improve their convergence properties. Several algorithms stand out among the multiobjective evolutionary algorithms that consider elitism, i.e., *the Strength Pareto Evolutionary Algorithm (SPEA* and *SPEAII)*, *the Pareto Archived Evolution Strategy* (*PAES)*, *the elitist GA of Rudolph*, *Pareto Envelope-based Selection Algorithm (PESA* and *PESA II*) and *Non-dominated Sorting Genetic Algorithm (NSGA II*).
This work uses the elitism-based *SPEA* method. Uniform crossover and non-uniform mutation were adopted for this work, following an analysis of the results of several tests using various different operators [7].

3. DEFINITION OF THE OBJECTIVE FUNCTIONS

Focusing on the development of a flexible tool that is easily handled by operators and clearly providing a set of operational rules according to the working conditions, part of the macro piping system of Goiânia, Brazil, was considered for analysis and evaluation of the results. For a clearer picture of the proposed application a diagram is shown of the system under study (Fig. 1), with its main characteristics (Table 1).
Several objectives can be listed when one evaluates a real water supply system in order to reach its optimal operation. One of the hypotheses is to evaluate the operational cost, including the system's maintenance and operation, collecting data about all the mechanical and hydraulic parameters relevant to this evaluation.



** nd - nonzero demand

Fig. 1 – Diagram of the macro system of Goiânia, Brazil

Studies developed in the past showed that, of all the parameters relating to this issue, the most relevant one is the cost of electrical energy consumption at water pumping stations. Another possibility is the system's reliability in meeting consumer needs coherently. In this case, several parameters can be listed. The reliability of water supply systems can be considered from a hydraulic or mechanical standpoint. The former involves the physical parameters, which vary according to operational changes in the system, while the latter involves the possible interventions on equipment [8]. Likewise [9], this work evaluates two basic objectives, the economic objective and the objective of hydraulic benefits of the water distribution systems.
In the case of the economic objective, the intention is to minimize the costs of electrical energy consumption at the pumping stations.

Table 1 – Goiânia Macro System – Pump and Tank Data

Flow(l/s)	Pumps	Head(m)	Tanks	Volume (m^3)	Min. Level	Max. Level	Elevation
895	26	85	14	10,000	1.5	6.0	858.0
895	27	85	19	5,000	1.5	5.5	861.5
895	28	85	24	10,000	1.5	7.0	836.5
			29	3,000	1.5	5.0	863.0

The daily cost for each pump at a pumping station is given by the sum of the cost of the maximum demand factor and the measured cost of consumption.

Considering the electrical energy costs to operate the pumping stations as an objective function, one has the following expression:

$$FO\_1 = [\ \sum_{t=1}^{24}\sum_{k=1}^{np} Cu(t) * \frac{Q(t,k) * H(t,k) * \gamma}{\eta(t,k)}\ ] + D * Rate$$

where k is the number of pumps at the pump station, t is time(h), $Cu(t)$ is the unit cost of the rate($R\$/kWh$), $Q(k,t)$ is the pumped outflow(m^3/h), $H(k,t)$ is the hydraulic head(m), $\eta(k,t)$ is the yield of the set(%), *D* is the maximum demand factor(kW), and *Rate* is the rate of maximum demand factor(*R$/kW*).

Three hydraulic parameters of the system were evaluated as benefit attributes: level of response to pressures at the demand nodes; minimum levels in the tanks; and the degree to which the demands are met. Based on [10], it was decided to adopt an optimal performance index to evaluate the hydraulic benefits. In this work, the quality of the water and the mechanical reliability were not considered, although their importance in the operational optimization of the system is recognized.

To consider the benefit of meeting the pressures at the demand nodes, it was used the index called, the pressure adequacy benefit (ψ_{pb}), using the following equation :

$$\psi_{pb(i,t)} = \left(\frac{P_{at(i,t)} - P_{mín}}{P_{req(t)} - P_{mín}} \right)^{1/2} \quad if \quad P_{mín} \leq P_{at(i,t)} \leq P_{req(t)}$$

$$\psi_{pb(i,t)} = 0 \quad if \quad P_{at(i,t)} < P_{mín} \quad or \quad P_{at(i,t)} > P_{req(t)}$$

where $P_{at(i,t)}$ is the actual nodal pressure (by EPANET), $P_{\min}$ is the minimum pressure (15m), and $P_{req(t)}$ is the maximum admitted pressure(time t).

The hydraulic benefit in terms of adequate nodal pressure (HB_{NP}), will be calculated by the following equation:

$$HB_{NP} = \sum_{t=1}^{24}\sum_{i=1}^{nn} \psi_{pb(i,t)}$$

As for the case of the benefit in terms of water levels in the tanks, it was used the index called the tank water level benefit (ψ_{lb}), as follows:

$$\psi_{lb(j,t)} = \left(\frac{N_{at(j,t)} - N_{mín(j)}}{N_{req(j,t)} - N_{mín(j)}} \right)^{1/2} \quad if \quad N_{mín} \leq N_{at(j,t)} \leq N_{req(j,t)}$$

$$\psi_{lb(j,t)} = 0 \quad if \quad N_{at(j,t)} < N_{mín} \quad or \quad N_{at(j,t)} > N_{req(j,t)}$$

where $N_{at(j,t)}$ is the tank water level at time *t*(by EPANET), $N_{\min(j)}$ is the minimum water level in the tank *j*, and $N_{req(j,t)}$ is the required water level in the tank *j* at the time *t*.

The hydraulic benefit in terms of adequate water levels in the tanks (BH_{WL}), will be:

$$HB_{WL} = \sum_{t=1}^{24} \sum_{j=1}^{nt} \psi_{lb(j,t)}$$

As for the demands, the hydraulic benefit(HB_{SD}), one has:

$$HB_{SD} = \sum_{t=1}^{24} \sum_{i=1}^{nn} \left(\frac{P_{at(i,t)} - P_{mín}}{P_{req(t)} - P_{mín}} \right)^{1/2} * \left(\frac{Q_{dem(i,t)}}{\sum_{i=1}^{nn} Q_{dem(i,t)}} \right)$$

where $Q_{dem(i,t)}$ is the hourly demand at the node *i* at time *t*, and $\sum_{i=1}^{nn} Q_{dem(i,t)}$ is the total hourly demand at time *t*.

Thus, the objective function of hydraulic benefits will be:

$$FO\_2 = HB_{NP} + HB_{WL} + HB_{SD}$$

Both the objectives (minimum cost and maximum benefits) defined by FO_1 and FO_2 are conflicting. So, trade-off solutions that define the set of non-dominated alternatives called the Pareto front have to be identified through multiobjective genetic algorithms.

4. REPRESENTATION OF THE SOLUTIONS

Each vector representative of a possible S1 solution for the system's operational strategy has the following characteristic:

$$S_1 = \left[\underbrace{P_{(0,1)}, P_{(0,2)}, P_{(0,3)}, V_{(0,4)}, V_{(0,5)}, V_{(0,6)}, V_{(0,7)}}_{Hour\ 0} \ldots\ldots \underbrace{P_{(23,1)}, P_{(23,2)}, P_{(23,3)}, P_{(23,4)}, P_{(23,5)}, P_{(23,6)}, P_{(23,7)}}_{Hour\ 23} \right]$$

where S_1 represents the solution vector, $P\ and\ V$ are the decision variables, $P_{(0,1)}$ is the status of pump number 1 at time zero (0/1=off/on), and $V_{(0,1)}$ is the status of the valve number 1 at time zero (0/1=closed/opened).

5. PROPOSED COMPUTATIONAL MODEL

A computational model was implemented which basically comprises two models: first, the hydraulic evaluation model, using Toolkit Library-Epanet2 codes and second, a multiobjective GA implementation model. The final parameters used in the optimization model were: uniform crossover, non-uniform mutation, population size=300, maximum number of generation=400, probability of crossover=0.9, and of mutation=0.006(1/number of decision variables).

6. RESULTS

The results obtained from application of the multiobjective genetic algorithm SPEA to the Goiânia's water distribution system are presented in this section in order to identify the final Pareto front (Fig. 2). This figure also indicates one randomly selected solution to show the main operational characteristics of the system when the operational rules are applied. The Fig. 3 and Fig. 4 present the tank water levels and pump operation for this random solution.

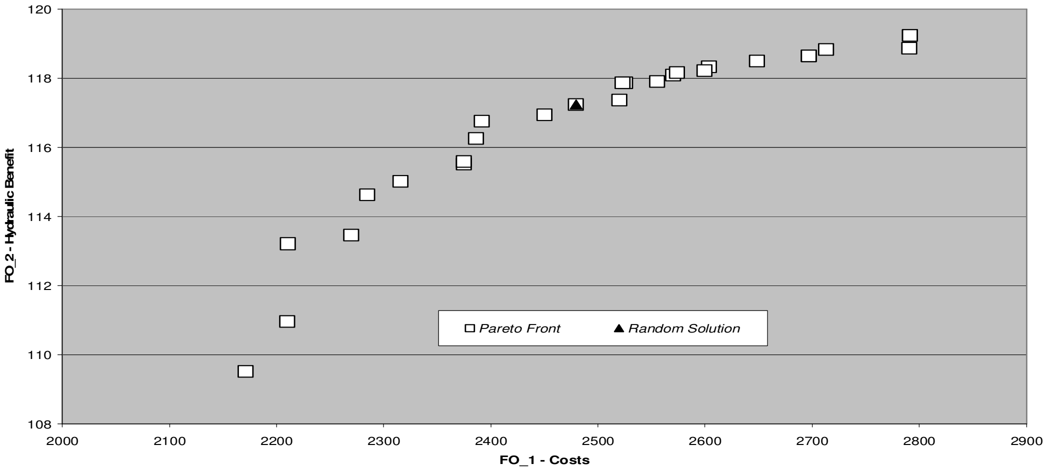


Fig. 2 – Goiânia – Pareto Front – Optimal Solutions

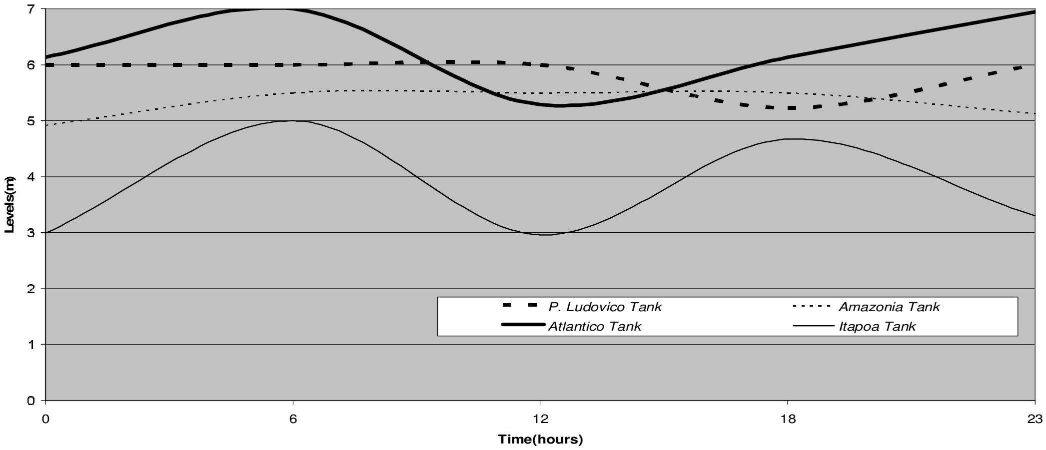


Fig. 3 – Water Tank Levels - Random Solution

1	2	3	4	5	6	7	8	9	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	**Time(hrs)**
□	□	■	■	□	□	■	□	■	■	■	■	□	□	□	□	■	■	■	■	□	■	■	□	**Pump 1**
■	□	■	□	□	□	□	■	□	■	□	□	□	□	□	■	□	■	□	□	□	■	■	□	**Pump 2**
□	■	□	□	□	□	□	■	■	■	□	□	■	■	■	■	□	■	□	□	□	■	■	■	**Pump 3**

■ **On**
□ **Off**

Fig. 4 – Pump Operation – Random Solution

7. CONCLUSIONS

This paper employs an elitist multiobjective evolutionary algorithm, called SPEA, to optimize the operation of a part of the Goiânia's Water Distribution System, evaluating the objectives of minimization of operational costs and maximization of hydraulic benefits, considering the index of demand met, adequate levels of water in the reservoirs, and minimum and maximum pressures at the demand points for a 24-hour period of analysis.

The results show good performance of the discovered model when applied in the Goiânia system. In order to obtain satisfactory results and to provide the operator proper conditions for the rational operation of the system, it is necessary choose a smaller number of solutions, and to extract those solutions specific rules to operation of the system. We leave this as an open topic for future research.

8. ACKNOWLEDGMENTS

The authors wish to express their gratitude to Saneamento de Goiás S.A. (Goiás State Sanitation Company)-SANEAGO S.A. for support to the first author of this work, including the one-year visit to Exeter University, UK, for which he is grateful also to the Centre for Water Systems. Support of Brazilian Research Council (CNPq) under the CT-HIDRO Program (process 550070/2002-8) is also acknowledged.

9. REFERENCES

[1] Zahed Filho, K. (1990) Previsão de Demanda de Consumo em Tempo Real no Desenvolvimento Operacional de Sistemas de Distribuição de Água, São Paulo, 135p.Tese(Doutorado), Escola Politécnica da Universidade de São Paulo, Brasil

[2] Luvizotto Júnior, E. (1995) Controle Operacional de Redes de Abastecimento de Água Auxiliado por Computador, São Paulo, 143p.Tese(Doutorado), Escola Politécnica da Universidade de São Paulo

[3] Righetto, A.M. (2002) Operação Ótima de Sistema Urbano de Distribuição de Água, In:Seminário-Planejamento, Projeto e Operação de Redes de Abastecimento de Água.O Estado da Arte e Questões Avançadas, João Pessoa, Brasil, CD-Rom, 16p.

[4] Rossman, L.A. (2001) EPANET2-Users Manual, U.S. Environmental Protection Agency, Cincinnati, Ohio

[5] Deb, K. (2001) Multi-Objective Using Evolutionary Algorithms, John Wiley & Sons, ltd.

[6] Deb, K., Pratap, A., Agarwal, S., and Meyarivan, T. (2002) A Fast and Elitist Multiobjective Genetic Algorithm:NSGA II, IEEE Transactions on Evolutionary Computation, 6(2), April, pp. 182-197

[7] Cheung,P.B. Reis, L.F.R. and Carrijo, I.B. (2003) Multiobjective Optimization to the Rehabilitation of a Water Distribution Network, Proc. International Conference on Computing and Control for the Water Industry,London, UK, Maksimovic,C., Butler, D., Memon,F., 315-325.

[8] Bao, Y and Mays, L.W. (1990) Model for Water Distribution System Reliability Journal of Hydraulic Engineering, v.116, n.9, pp.1119-1137

[9] Walters, G.A, Halhal, D., Savic, D., and Quazar, D. (1999). Improved Design of "Anytown" Distribution Network Using Structured Messy Genetic Algorithms Urban Water, v.1, pp. 23-38

[10] Tanyimboh, T.T., Tabesh, M., and Burrows, R. (2001) Appraisal of Source Head Methods for Calculating Reliability of Water Distribution Networks Journal of Water Resources Planning and Management, v.127, n.4, July-August, pp. 206-213