

OPTIMIZING THE PUMP OPERATIONS IN A WATER DISTRIBUTION SYSTEM BY MINIMIZING THE ENERGY AND MAINTENANCE COSTS

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Introduction

Modeling and solving a Pump Scheduling Problem (PSP) focuses on achieving the conservation of electrical energy which is the main element to the operational cost in a water distribution system. The optimal pump-schedule is used to select the best combination of pumps that will be running at each time interval during an optimization period. This minimizes the energy consumption and maintenance cost of the system while satisfying the hydraulic and system constraints. In this context, the operational cost of the system will be optimized with the existing infrastructure and therefore, no additional cost is incurred for the implementation.

Most of the approaches to solve PSP have been considered to optimize the scheduling of pumps with a single objective function (cost of energy consumption) subject to the set of constraints. The electric energy cost can be reduced by turning a pump on and off many times during the optimization period according to the Optimal Pump Schedule (OPS). On the other hand, this OPS may increase the wear on the pumps and will result in increased pump maintenance costs. It can be assumed that the maintenance cost increases linearly as the number of pump switches increases. Hence, the number of pump switches is used as a surrogate

measure for the intangible wear-and-tear cost (Lansley and Awumah, 1994).

The main objective of this study is to establish a mathematical programming model to minimize the energy cost for pumping subject to the system constraints, while limiting the number of pump switches. The other objective is to find a suitable algorithm to obtain the optimal solution with a less computational time. Finally, the paper discusses about the use of this type of OPS with the results of data obtained from an existing water distribution system.

Problem Definition

There are two types of costs associated with the PSP of a water distribution system: electrical and maintenance costs. The electrical energy cost is the cost of energy consumed by pumps during an optimization period. Maintenance costs are mainly related with the wear and tear of pumps (future repairs and replacements). A typical water distribution system in Sri Lanka consists of one reservoir (storage tank), one drinking water source and a set of fixed speed pumps. The optimization period is set to one day which is divided into intervals of one hour intervals. Feasible solutions of the OPS problem is coded with binary numbers which gives the state

(on/off) of each pump combination during a particular time interval. This combination of pumps will supply water from the sources to the elevated reservoir, from which the consumer demands are drawn. The proposed objective function (1) is based on the electrical tariff structure imposed by the Ceylon Electricity Board. The water volume of the storage tank must be operated within a minimum (*LV*) and a maximum (*UV*) volumes. The volumes of water in the tanks at the end of each time interval should not be less than the demand of the successive interval in order to achieve periodicity between supply and demand.

Formulation of the Mathematical Model

The Mathematical model of the PSP presented by Gomezs et al is modified and used in this study (Gomezs and Daundasekera, 2009). The pump maintenance cost can be reduced indirectly by minimizing the number of pump switches, since switching is not quantifiable as a cost. Therefore, the switching objective is introduced into the model as a constraint (Equation 2). The objective function of the modified model:

Minimize cost of consumed energy:

$$C_L \sum_{i=1}^{17} \sum_j^P X_{ij} E_j + C_H \sum_{i=8}^{22} \sum_j^P X_{ij} E_j + C_L \sum_{i=23}^{24} \sum_j^P X_{ij} E_j \quad (1)$$

where, *i*= time interval index, *j* = pump combination index, X_{ij} =*j*th pump combination activates in the *i*th time interval, *E_j*= consumed electricity of the pump combination *j*, *P* = Number of pump combinations, *C_L*=unit charge of electrical energy in the low

cost period, *C_H* = unit charge of electrical energy in the high cost period.

The following operational constraints are taken into consideration to formulate the model:

To restrict the pump wear-off cost to tolerable level, the number of pump switching should be less than an acceptable value. Thus, the constraint (2) is incorporated into the model:

$$\sum_{i=1}^{24} \sum_j^P SWC_j X_{ij} \leq MSW, \quad (2)$$

where *SWC_j* = Number of pump switches for pump combination *j*, *MSW*= constant to be specified and it is the number of pump switches allowed for the optimization period.

The volume in each time interval (*V_i*) can be expressed as:

$$V_i = \begin{cases} V_0 + WP_{ij} - D_i & i = 1 \\ V_{i-1} + WP_{ij} - D_i & i = 2, \dots, 24 \end{cases} \quad (3)$$

where, *WP_{ij}* = pumped volume of water using *j*th combination in the *i*th interval, *D_i*= consumers' water demand in the *i*th time interval, *V₀*= initial volume. The bound on the water volume of the tank in the *i*th time interval:

$$LV \leq V_i \leq UV \quad (4)$$

Since only one pump combination can be activated for a given one hour time interval,

$$\sum_{j=1}^P X_{ij} = 1; X_{ij} \in \{0, 1\}; i = 1, \dots, 24 \quad (5)$$

It is a request that the total volume deficit should be zero. That is,

$$\sum_{i=1}^{24} \Delta V_i = 0, \text{ where,} \quad (6)$$

$$\Delta V_i = \begin{cases} V_i - UV & i = 1 \\ V_i - V_{i-1} & i = 2, \dots, 24 \end{cases}; LV \leq \Delta V_i \leq UV$$

Methodology

Volume of water pumped into the reservoir should be equal to the consumers' demand in each time interval. Therefore, the model minimizes number of pump switches while satisfying consumers' demand. It can be noticed that the above model is a single objective linear model where the decision variables (X_{ij}) are binary integers. The formulated model can be identified as Integer Linear Programming (ILP) and hence, the Branch-and-Cut algorithm is applied to solve the model. With the help of GNU linear programming kit, the Branch-and-Cut algorithm was coded to solve ILP. The model was solved repeatedly while increasing the number of pump switches and monitoring the optimum solution until an infeasible solution is reached.

The Case Study

The data obtained from the Badulla municipal water distribution system is used to test the applicability of the model and the programme. The system consists of one tank ($LV = 200m^3$, $UV = 1000m^3$) and three fixed speed pumps.

The model has 192 decision variables ($2^3 \times 24$). The daily consumer demand profile of the considered water distribution system is graphed in Figure 1.

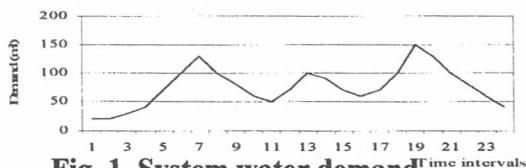


Fig. 1. System water demand^{Time intervals}

Results and Discussion

The analysis of the implementation of the OPS in the given system was performed considering the allowable

number of pump switches. The minimum costs of the OPSs are computed and corresponding monthly cost and savings are recorded. Monthly electricity cost for the month of October 2009 is Rs 385,136.00. It can be observed that the minimum cost of the OPS increases when using small number of pump switches. It is clear that there will be a lower bound of 12 for *MSW* to operate the system for given set of demand.

Conclusion

The results obtained from the case study have demonstrated that significant cost reduction can be achieved by limiting the number of pump switches. *MSW* = 16 would be an appropriate for the given system because minimum energy cost is less than value of the *MSW* = 17.

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References

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