Pump Scheduling Optimization Model for Water Supply System Using AWGA

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Abstract: *The water supply system has a high operational cost associated with its operations. This is characteristically due to the operations of the pumps that consume significantly high amount of electric energy. In order to minimize the electric energy consumption and reduce the maintenance cost of the system, this paper proposes the use of an Adaptive Weighted sum Genetic Algorithm (AWGA) in creating an optimal pump schedule, which can minimize the cost of electricity and satisfy the constraint of the maximum and minimum levels of water in the reservoir as well. The Adaptive weighted sum GA is based on popular weighted sum approach GA for multi-objective optimization problem wherein the weights multipliers of the individual fitness functions are adaptively selected. The algorithm has been tested using a hypothetical case study and promising results have been obtained and presented.*

Keywords: ***water supply system, Adaptive weighted sum Genetic Algorithm, Multi-objective Optimization.***

I. INTRODUCTION

Water is one of the most important basic commodity needed for survival and being used by virtual all for daily activities ranging from domestic to industrial activities. Therefore, to ensure adequate supply of water from the water supply system (WSS), much attention has been given to its operations to ensure it operates at a certain optimal level and satisfies the demand requirement at a minimum operational cost.

A typical water system consists of considerable number of pumps used to convey water to an elevated reservoir from wherein it supplies the consumer demand. Characteristically these pumps consumes significantly high amount of electric energy, which accrues to the operational cost. Most often the high operational cost is associated with the pumping activities [1]. S. Shu, *et al* in (2010) reported that about 700 million Euros is being expended annually on the pumping station in the UK, while in China about 30% to 50% of the total operational cost of the WSS is as a result of the electric cost spent on the pumps [2].

Numerous methods have been used to reduce the operational cost [3] by scheduling the operations of the pumps in the station. This method offers the most efficient and reliable method without making any infrastructural change to the system itself [4-5]. Hence, optimizing the schedule of the pumps is of great importance to the water industries, which offers up to about 10% reduction of the annual expenditure on energy and other related cost [6].

Most often the pumps are of different capacities and works in combination to deliver water from same or different water source through the main pipeline to the overhead elevated reservoir for onward supply to the consumers. Pump scheduling refers to the process of selecting sets of combination of pump amidst to be operated at a particular interval to deliver the required amount of water. However the combination of selected pumps must satisfy the particular objectives such as to minimize the amount of electric energy consumed and also to meet the system requirement like hydraulic and technical constraints and as well as the demand requirements.

The most prominent and important objective considered for optimization is the operating cost, which comprises of electric energy cost and the maintenance cost of the pumps. Basically the energy cost is composed of the demand and the electric consumption charges. The former is the cost associated with the maximum amount of power consumed within a period which most often is fixed and the latter is the cost of the electric energy consumed during a period of time defined by the $/KW-h. Most often, the price per unit of energy as defined by the supplier varies with time and known as the peak and off peak periods. The peak period usually is more expensive than the off peak period due to the high demand of energy at the peak time. For the maintenance cost, it is associated with servicing the wear and tear in the pumps as they run. The switch concept formulated by Lansey and Awumah [7] is used as a surrogate to measure the maintenance cost. As the number of switches turned increases the maintenance cost also increases.

Many researchers proposed scheduling methods for the WSS operating such as linear programming [8-9], non-linear programming [10-11], and dynamic programming [12-13]. However these methods are not satisfactory for all types of scheduling problems and sometime they become very difficult to use when the system size and constraints increases. Lately the use evolutionary computation algorithms especially Genetic Algorithm (GA) to create optimal scheduling system has been increased due to the development of high performance processor and computing methods. The simple single objective GA has been proposed by [14] for the minimization of the electric energy cost. Multi-objective algorithms using GA have also been developed to optimize the WSS system by considering other objectives such as the maintenance cost, peak power, level variation [1,4] and environmental factor [5].

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All of the aforementioned works with respect to the pump scheduling problem based on the Evolutionary Genetic Algorithm used Pareto approach technique. This work proposes the use of Adaptive weighted Genetic Algorithm (AWGA) to solve the pump scheduling problem with the objective to minimize the electric energy cost and the maintenance cost. The AWGA is based on the weighted sum approach, which is one the most prominent approach for evaluating GA that has never been used for solving this problem. Finally, the performance of AWGA is compared with others approach such as simple fix weight GA (FWGA) [15] and random weight GA (SOGA) [16].

II. CASE STUDY AND MODELING OF PUMP SCHEDULE

The main aim of this work is to use the AWGA to solve the problem of pump schedule for the water supply station for a model as shown in Fig.1 that proposed by [4]. This system uses 5 different types of fixed pumps. A few assumptions are considered during the optimization as follows:

a) That the system consists of a n defined number of fixed speed pumps whose flow capacities $Q(m^3/h)$ and power ratings $P(KWh)$ are constant over the optimization period.

b) That the elevated reservoir storage capacity is well defined with maximum $h_{\max}(m)$ and minimum $h_{\min}(m)$ level limits and also can satisfy the demand requirement.

c) That the approximated model is able to satisfy all the system requirements (such as the hydraulic requirement) as well as the demand requirements.

Fig. 2 shows the average of water demand profile per hour for one day. In order to formulate a multi-objective optimization problem for the pump schedule, the objective functions to be optimized are defined as energy cost and maintenance cost based on the demand.

A. Energy Cost

The energy cost of the water supply system is defined as a cost of the electric energy consumed by the operating pumps in the system over the schedule period and it is influenced by the power rating of the pumps as well as the electric charge tariff plan stipulated by the energy utility company.

The electric charge tariff most often varies between the off-peak and peak period, with the off-peak been less expensive than the peak period. For this work the electric charge tariff C_c is defined as follows, off peak period charge C_{cl} (2200 to 0800) and Peak period charge C_{ch} (0800 to 2200). The equation for the electric energy cost is defined as shown in (1).

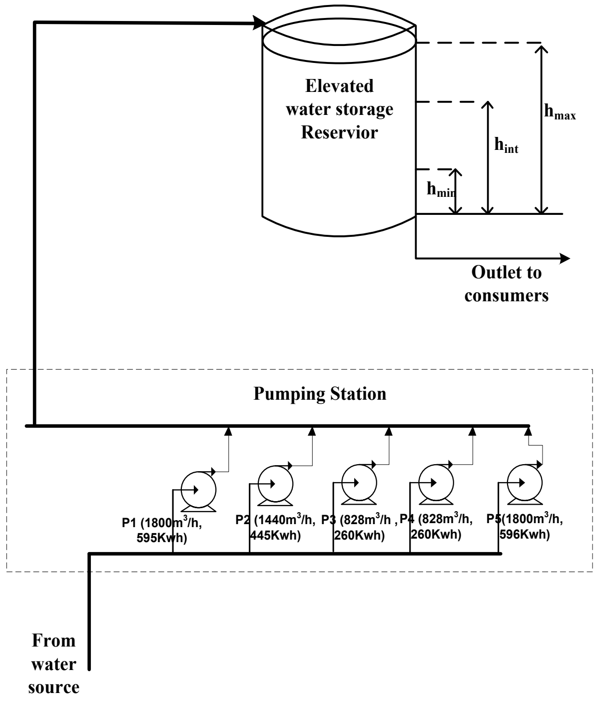

Figure 1. The water supply system model

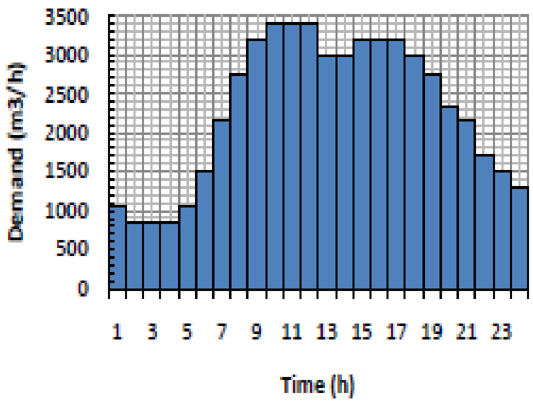

Figure 2. The water demand profile

$$E_c = C_{cl}\sum_{i=1}^{8} e(P_i) + C_{ch}\sum_{j=9}^{22} e(P_i) + C_{cl}\sum_{j=23}^{24} e(P_i) \quad (1)$$

where

C_{cl} is the OFF-peak tariff price
C_{ch} is the peak tariff price
P_i is the combination of pumps operation at interval i
eP_i is the electric energy consumed by the pumps at interval i

B. Maintenance Cost

The Maintenance cost is another factor that influences the operational cost of the water supply system. However, it is very difficult to quantify as it involves the measure of the wear and tear in the pumps. The switch concept [11] is used as a surrogate of the maintenance cost, as the switch turned increases the maintenance cost also increases. The number of switch N_s, is computed using (2), with each pump associated with a switch and the switch is considered on if and only if the pump was turned off is on at the current time interval but off at previous interval.

$$N_s = \sum_{i=1}^{N}\sum_{j=1}^{T}\left|P_s^{j+1} - P_s^{j}\right| \qquad (2)$$

where

P_s^{j+1} is current state of the pump

P_s^{j} is the previous state of the pump

N_s is the total number of switches turned by N pump

T duration time the pump in operation

C. Model Constraint

The maximum and minimum levels of the water in the reservoir are considered as the model constraints, such that the level of the water in the reservoir does not exceed the specified maximum height $h_{\max}$ else results in wastage of resources and the minimum level $h_{\min}$ is always exceed to ensure that the system will always satisfy emergency requirements (provision of water for firefighting situations). The minimum and maximum level constraint is expressed by (3) with h_j been the water level at any interval in the optimization period.

$$h_{min} \le h_j \le h_{max} \qquad (3)$$

where

$$h_j = h_{j-1} + \frac{(Q_j - D_j)}{A} \qquad (4)$$

h_{min} is the minimum storage level

h_{max} is the maximum storage level

h_j is the level at interval j

h_{j-1} is the level at previous interval before j

Q_j is the amount of water pumped at interval j

D_j is the amount of water demand at interval j

A is area of the storage tank

III. SOLUTION METHODOLOGY (THE ADAPTIVE GENETIC ALGORITHM)

Fig. 3 describes the entire procedure of the proposed AWGA for the problem of creating optimal pump schedule. The AWGA process starts with the encoding of the decision variables (the pumps) to form the chromosomes that represent the possible solutions to the problem. The binary coding technique is used to encode the pumps with a '1' signifying an ON state and '0' signifying an OFF state for each of the pumps in the schedule interval. A total number of 120 bits is used to encode a chromosome. The first step of the Algorithm creates the initial population of chromosomes. The chromosomes are created such that they satisfy the constraint of the problem, and any chromosome that does not satisfy the constraint are discarded and replaced until the required number of chromosomes for the initial population is completed.

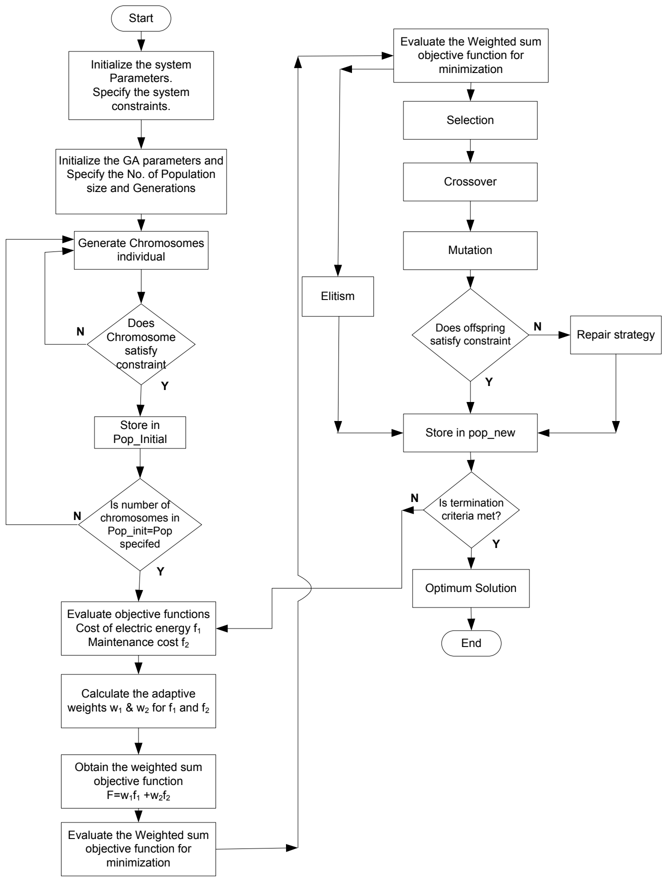

Figure 3. The flowchart of the proposed AWGA

The fitness functions are applied to the chromosomes in the initial population for the determination of their fitness values. Based on these fitness values the adaptive weights multiplier of each of the objective function are determined as given in in Table 1, thereafter used to form the weighted sum objective function. The adaptive weights formulation relies heavily on the information of the current fitness values of the chromosomes thereby making them change adaptively in every iteration of the AWGA. Furthermore this approach ensures that no one single objective function completely dominates the other in their combination to form the total weighted sum fitness function which is then subjected to the selection, crossover and mutation of the AWGA.

Upon the completion of the mutation operation the newly formed offspring are passed through the repair strategy. This is to ensure that the chromosomes of the newly formed offspring are repaired to meet the constraint requirements if they do not and that only feasible solutions are seeded to the next generation of the AWGA. The steps for repair strategy are as follows:

If { newly created offspring's chromosomes violates the level constraint
Step 1: Initialize repair activator counter
Step 2: Discard offspring
Step 3: Repeat the crossover process with the same parents and then do mutation
Step45: Check newly created offspring for level constraint
Step 5: If { the level is satisfied, move offspring to the next generation population Step 9
Step 6: Else { increment repair activator counter and discard offspring Step 3
Step 7: If { repair activator counter ≥ number of genes in a pump unit
Step 8: Initiate repair strategy
Search for interval with violation
If overflow switch OFF one or more pumps until level constraint is satisfied
Else under overflow switch ON one or more level constraint is satisfied
Move repaired offspring to the next generation population
Step 9: Next generation population

The elitism is another strategy placed in the Algorithm to ensure that two of the current best chromosomes of a generation make it through to the next generation.

TABLE 1. THE ADAPTIVE WEIGHT DETERMINATION PROCESS

Evaluate the objective functions (1) and (2) for each of the chromosomes in the initial population to obtain the fitness values $f(E_C), f(N_S)$.
From the fitness values determine $Z_1^{max} = \max f(E_c)$, $Z_1^{min} = \min f(E_c)$ $Z_2^{max} = \max f(N_s)$, $Z_2^{min} = \min f(N_s)$.
Determine the weight values $w_1 = \frac{1}{(Z_1^{max} - Z_1^{min})}$, $w_2 = \frac{1}{(Z_2^{max} - Z_2^{min})}$.
Evaluate weight sum objective $f(E_c N_s) = w_1 f(E_c) + w_2 f(N_s)$.

IV. RESULTS AND DISCUSSION

The Adaptive Weight Genetic Algorithm for the pump schedule problem is been implemented using MATLAB programming Language 2010b and a PC with Intel(R) Core(TM) i5-2410M CPU @ 2.30GHz, 4GB RAM. The algorithm has been simulated under varying system conditions such as different levels of water in the reservoir and was to able handle varying system conditions..

The algorithm parameters such as population size, mutation rate, and crossover rate as stated in the Table 2. These parameters were selected based on the performance of the algorithm after several trials in order to obtain suitable parameters in this application.

The program was ran for more than 30 times in order to ascertain the repeatability of the algorithm in determining the an optimal solution to the problem. The performance of the total weighted fitness function minimizing the 2 objective functions stated earlier in section II for the best 6 of the trials are presented in Fig. 4. The result shows that Trial 5 produces the best convergence in minimizing the objective function as compared to others, with a total pumping cost (electric energy and maintenance costs) of 4372RM with a cumulative number of 10 switches turned in the entire schedule and also satisfying the level constraint in the reservoir. All other trials obtained within 3.30% of the best solution of trial 5.

TABLE 2. THE MODEL PARAMETERS

Model Parameters	
Parameter Description	***Values***
Maximum height in reservior h_{max}	7m
Minimum height in reservior h_{min}	1m
Initial height in Reservior $h_{initial}$	3m
Off peak period tariff C_{Cl}	0.2496RM
Peak Period tariff C_{Ch}	0.3120RM
Number of population	100
Number of Generations	5000
Elite count	2
Mutation rate	0.05
Crossover rate	0.4
Selection type	Roulette Wheel

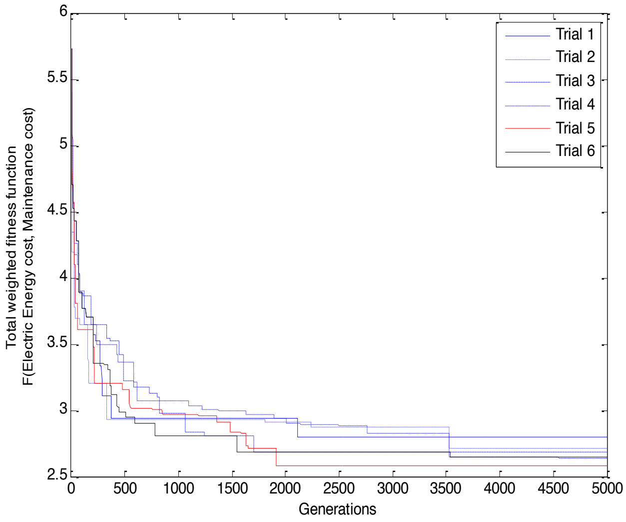

Figure 4. The performance of the AWGA

Furthermore to investigate the quality of solution produced by the AWGA, two other types of weighted sum algorithm FWGA and SOGA were simulated. The comparison is based on a performance index, which is percentage difference between the total operational cost (electric energy cost and maintenance cost) obtained on the first iteration and that of the last iteration of the Algorithm. The result is shown in Fig. 5 and the summary of the performance is listed in Table 3. For the FWGA, the weightage for cost of electrical energy and cost of maintenance are 60% and 40% respectively. The results show the AWGA having the highest percentage of 16.2% next to the FWGA with 7.23% and then the SOGA with 7.74%, this shows the ability of the AWGA to minimize the fitness functions over the iteration of the process with its adaptive weights.

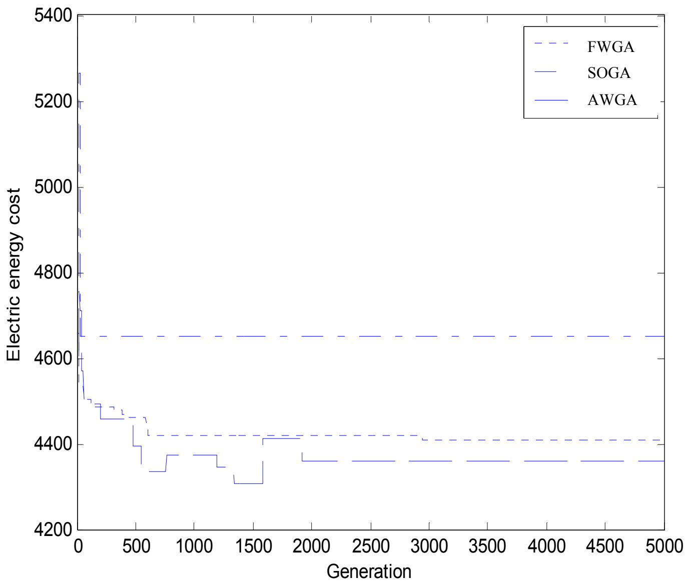

Figure 5. The performance comparison

TABLE 3. THE COMPARISON RESULTS

Comparison Results			
Algorithms	***Initial Cost***	***Final Cost***	***Performance Index %***
FWGA	4770	4425	7.23
AWGA	5218	4372	16.2
SOGA	5067	4675	7.74

V. CONCLUSIONS

In this paper, an optimal pump-scheduling problem using the Adaptive Weight Genetic Algorithm (AWGA) has been presented. The proposed Algorithm has been tested using hypothetical data from other supply station and has shown the ability to achieve optimum pump schedule that would minimize the overall operation cost of the system. One advantage, of this proposed method as shown above is in its ability to obtain an optimal solution over a iterations of the process and also in its computational time as it does not need to search for dominating and non-dominating solutions in order to determine the optimal solution. Although the algorithm, could achieve a minimum number of switch over a schedule period, however some improvement may be required to make it more robust such as placing a restriction on the number of switch that can be turned, and also considering more possible objectives.

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