APPLICATION OF HONEY-BEES MATING OPTIMIZATION ALGORITHM TO PUMPING STATION SCHEDULING FOR WATER SUPPLY

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Pumping station scheduling for variable water supply can be optimised by using the Honey Bees Mating Optimization Algorithm (HBMOA), a swarm-based approach, where the search procedure is inspired by the process of mating in a real honey bee colony. The HBMOA form applied in this paper, denoted HBMOA-M1, is modified with respect to the classical formulation: the solutions improved during the current iteration, ranked after the queen as fitness, are inserted within the list of drones for the next iteration. That approach improves clearly the computational efficiency, and gives better results than the classical one. In this paper, HBMOA-M1 has been tested on a simple pumping station model, equipped with variable speed pumps. The optimization process yielded the speed values of each pump, for parallel pump functioning at an imposed operation point (given pumping station head and flow rate), corresponding to the minimization of power consumption (objective function), while satisfying hydraulic constraints with penalty functions approach.

Keywords: Honey Bees Mating Optimization Algorithm, swarm-based approach, pumping station scheduling.

1. Introduction

In water distribution systems, one of the greatest potential areas for energy cost-savings is the scheduling of daily pump operations. Typically, a water supply system is composed of several pumping stations, which supply reservoirs (storage tanks) from where water flows towards the distribution network, or supply simultaneously reservoirs and network. Such pumping stations are equipped with different pumps that operate in parallel, with variable speed, upon the variable water demand; some pumps may run, while others may not. A pump schedule is the set of many combinations of pumps operation parameters, which should be selected for every time interval, to fulfil system restrictions regarding: the cost of the energy consumed for pumping, the maximum power peak (cost of reserved power [1]), the pumps maintenance cost, the level variation in reservoirs between imposed upper and lower limits, the water demand, technical characteristics of pump combinations etc.

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Various stochastic methods for combinatorial optimization can be applied to solve optimal pump-scheduling problems, by minimizing or maximizing the objective function, while satisfying system constraints, with randomness within the search process. Among them, the Simulated Annealing Algorithm (SAA) [2], or some evolutionary algorithms, like Genetic Algorithms (GA) [3], Ant Colony Optimization Algorithm (ACOA) [4], and Honey Bees Mating Optimization Algorithm (HBMOA) [5], were successfully used to find optimal schedules for pumps. Multi-objective evolutionary algorithms were used [6], [7] to analyse several simultaneous objectives of pump-scheduling problems.

HBMOA is a swarm-based approach, where the search procedure is inspired by the process of mating in a real honey bee colony. In the classical form of HBMOA [8], all solutions generated and improved during the current iteration (excepting the best solution – the queen bee) are completely destroyed at the end of the iteration, and a new swarm of solutions (drones) is randomly generated for the next iteration. The modified HBMOA formulation [9], [10] applied in this paper, denoted HBMOA-M1, uses the solutions improved during the current iteration, ranked after the queen as fitness (performance), and inserts them within the list of drones for the next iteration, thus improving the colony genes in the coming generation. HBMOA-M1 has been successfully implemented to hydraulic networks design optimization: e.g. for Hanoi water distribution network test-case, Popa & Georgescu [10] showed that HBMOA-M1 improves the computational efficiency, and gives better results than the classical HBMOA, as well as than ACOA, SAA, and various formulations based on GA.

In this paper, HBMOA-M1 has been implemented to determine optimal schedule for pumps, within a simple pumping station model, equipped with two identical centrifugal pumps, with variable speed. The optimization process yielded the speed values of each pump, for parallel pump functioning at an imposed operation point (given pumping station head and flow rate), corresponding to the minimization of power consumption (objective function), while satisfying hydraulic constraints with penalty functions for restrictions violation. The results encourage us to implement HBMOA-M1 in further work, for complex problems, i.e. to optimize pumps schedules for a water distribution system, involving several pumping stations and reservoirs.

2. Pumping station model

The studied pumping station (PS) model is established based on the following simplified assumptions:

- PS is equipped with 2 identical centrifugal pumps; each pump *i*, with $i = 1; 2$, has a variable speed $n_i \in [n_{min}; n_{max}]$; usually, $n_{min} = 0.7 n_0$ and $n_{max} = n_0$, where n_0 is the nominal speed of the pump; we will consider the case $n_1 > n_2$;

- the pump head curve $H = H(Q)$, and efficiency curve $\eta = \eta(Q)$ are given at the nominal speed n_0, as 2nd order polynomials, with known coefficients $c_0 \div c_5$;
- head losses in pipes are computed with Darcy-Weissbach formula, where the friction factor λ is defined for fully turbulent flow;
- the pumps are coupled in parallel, each pump being mounted on a pipeline of length L_i and diameter D_i, connected upstream to a common distribution node, and downstream to a collector node; the hydraulic resistance modulus of each pipeline $M_i = 0.0826\lambda_i L_i / D_i^5$ is constant, as for fully turbulent flow;
- the hydraulic system supplied by SP has a constant hydraulic resistance modulus M; the system static head H_s is also constant. The system head curve is: $H_{hsys} = (H_s + M\,Q_{hsys}^2)$, so the flow rate through the system can be expressed as:

$$Q_{hsys} = Q_{hsys}\left(H_{hsys}\right) = \sqrt{(H_{hsys} - H_s)/M}\ . \tag{1}$$

The pump reduced head curve is defined for $i = 1$ and $i = 2$, as [11]:

$$H_{red_i} = \left(n_i/n_0\right)^2\left(c_0 + c_1 Q + c_2 Q^2\right) - M_i Q^2\ . \tag{2}$$

Since we assumed $n_1 > n_2$, according to (2): $H_{red1}(0) > H_{red2}(0)$ at $Q = 0$. For a certain flow rate value Q_i^*, the efficiency of pump *i* operating at $n_i \neq n_0$ is:

$$\eta_i = c_3 + c_4\left(n_0/n_i\right)Q_i^* + c_5\left(n_0/n_i\right)^2 Q_i^{*2}\ . \tag{3}$$

The pumping station head curve $H_{PS} = H_{PS}(Q_{PS})$ can be graphically obtained by adding in parallel the curves $H_{red_i} = H_{red_i}(Q)$ for $i = 1$ and $i = 2$, meaning by adding the flow rate values deduced from the two curves (2), for constant values of H_{red_i}. If the PS head is ranged as $H_{red2}(0) \le H_{PS} \le H_{red1}(0)$, then $H_{PS} = H_{red1}(Q_{PS})$, and the flow rate delivered by PS, $Q_{PS} = Q_{PS}(H_{PS})$, is:

$$Q_{PS} = \left(-1 + \sqrt{1 - 2d_1(c_0 - H_{PS}\left(n_0/n_1\right)^2)/c_1}\right)\Big/ d_1\ , \tag{4}$$

where d_1 is defined by $d_i = 2\left(c_2 - M_i\left(n_0/n_i\right)^2\right)/c_1$, for $i = 1$. If the PS head is ranged as $H_s \le H_{PS} \le H_{red2}(0)$, then $Q_{PS} = Q_{PS}(H_{PS})$ delivered by PS is:

$$Q_{PS} = \sum_{i=1}^{2} \left[\left(-1 + \sqrt{1 - 2d_i (c_0 - H_{PS} (n_0 / n_i)^2) / c_1} \right) \Big/ d_i \right]. \tag{5}$$

For the above two pumps, operating in parallel within the PS to supply the hydraulic system, the operating point *A* of the pumping station is defined at the intersection between the pumping station head curve $H_{PS} = H_{PS}(Q_{PS})$, and the system head curve $H_{hsys} = H_{hsys}(Q_{hsys})$, so at that intersection point *A*, we obtain: $Q_A = Q_{PS}|_A \equiv Q_{hsys}|_A$ and $H_A = H_{PS}|_A \equiv H_{hsys}|_A$. The value of pumping station head in *A* is obtained by solving the equations $f_a(H_A) = 0$ and $f_b(H_A) = 0$, as:

$$f_a = \frac{-1 + \sqrt{1 - 2d_1 (c_0 - H_A (n_0 / n_1)^2) / c_1}}{d_1} - \sqrt{\frac{(H_A - H_s)}{M}} = 0, \tag{6}$$
if $H_{red2}(0) \le H_A \le H_{red1}(0)$

$$f_b = \sum_{i=1}^{2} \frac{-1 + \sqrt{1 - 2d_i (c_0 - H_A (n_0 / n_i)^2) / c_1}}{d_i} - \sqrt{\frac{(H_A - H_s)}{M}} = 0. \tag{7}$$
if $H_s \le H_A \le H_{red2}(0)$

where $H_{red_i}(0) = c_0 (n_i / n_0)^2$ for $i = 1; 2$. Within the studied pump-scheduling problem, the decision variables (unknowns of the optimization problem) are the two values of pump speed: n_i. The two speed values n_1 and n_2 are randomly generated within the range $[n_{min}; n_{max}]$. Eqs (6) and (7) are solved as follows:

$$\begin{cases} \text{if } f_a(H_{red1}(0)) \cdot f_a(H_{red2}(0)) < 0 \Rightarrow \text{eq.(6) is solved} \\ \text{if } f_b(H_{red2}(0)) \cdot f_b(H_s) < 0 \qquad \Rightarrow \text{eq.(7) is solved} \end{cases}. \tag{8}$$

After obtaining the PS head value H_A at the operating point *A*, the total flow rate delivered by PS is computed as: $Q_A = \sqrt{(H_A - H_s)/M}$. The flow rate values Q_{Ai} delivered by each pump $i = 1; 2$ are obtained by solving: $H_A = H_{red_i}(Q_{Ai})\big|_{\text{eq.(2)}}$. The head H_{Ai} of the pump that delivers the flow rate Q_{Ai} can be computed as: $H_{Ai} = (H_A + M_i Q_{Ai}^2)$. Each pump efficiency η_{Ai} is obtained from (3), where

$Q_i^* \equiv Q_{Ai}$. With all data attached to the operation point A_i of each individual pump, the power consumption of each pump is defined as: $P_i = \rho g Q_{Ai} H_{Ai} / \eta_{Ai}$ where ρ is the water density and g is the gravity. Each power P_i ($i = 1; 2$) is the output mechanical power of the electrical motor that drives the pump.

A simple objective function F consists of minimizing the total power consumption P, while satisfying hydraulic restrictions, expressed by sets R_a or R_b:

$$F = \min\{P\} = \min\left\{\sum_i P_i\right\} = \min\left\{\sum_i \left(\rho g Q_{Ai} H_{Ai} / \eta_{Ai}\right)\right\}, \tag{9}$$

$$R_a = \begin{cases} 0.7 n_0 \le n_i \le n_0 & \\ Q_A = \sum_i Q_{Ai} = Q^* & \text{(requested total flow rate)} \\ H_A \ge H^* & \text{(minimum PS head)} \end{cases},$$
$$R_b = \begin{cases} 0.7 n_0 \le n_i \le n_0 & \\ H_A = H^* & \text{(requested PS head)} \\ Q_A = \sum_i Q_{Ai} \ge Q^* & \text{(minimum total flow rate)} \end{cases} \tag{10}$$

where Q^* is the requested total flow rate that must be delivered by PS, and H^* is the requested PS head at the operation point A. The objective function with penalties used in this paper consists of minimizing the total power consumption of PS (in watt), while satisfying hydraulic constraints (10) with penalty functions, as:

$$F = \min\left\{10^{-2} \sum_i P_i + p_1 \left|Q^* - Q_A\right| + p_2 \left|H^* - H_A\right|\right\}$$
$$\text{where } p_1 = \begin{cases} 10^6 & \text{if } Q_A < Q^* \\ 0 & \text{if } Q_A \ge Q^* \end{cases}, \text{ and } p_2 = \begin{cases} 10^5 & \text{if } H_A < H^* \\ 0 & \text{if } H_A \ge H^* \end{cases}. \tag{11}$$

where p_1 and p_2 are penalty coefficients for restrictions violation. The performance function F_p used in HBMOA-M1 is: $F_p = 200/F$.

The pumping station model described in this section can be generalized to a greater number of identical pumps operating in parallel, i.e. N pumps. The first step is to rank decreasingly the values $H_{red_i}(0) = c_0 (n_i / n_0)^2$, for $i = 1 \div N$. Then, pumping station head curve must be generated using different equations like (5), where $i = 1 \div N$, applied successively from top to bottom, for different head steps.

3. Honey Bees Mating Optimization Algorithm parameters

Within Honey Bees Mating Optimization, the search algorithm is inspired by the process of mating in a real honey bee colony. The HBMO algorithm has been fully described in Popa & Georgescu [10]. We will add here only data attached to the studied optimization problem, namely data used within the HBMOA-M1 formulation, to determine the optimal schedule for pumps that operate in parallel within a pumping station. Within this paper, a solution (bee) has a number of unknowns (genes) equal to the total number of pump speed values n_i (where $i = 1; 2$ for the simple PS model from Section 2, or $i = 1 \div N$ if the PS is equipped with *N* pumps). There is a difference between the HBMOA steps described in Popa & Georgescu [10], and the present paper: we used here a different non-uniform mutation operator than in [10]; here, the value v_{ij} of the gene *j* (one variable from bee's genome), selected for mutation, is modified to:

$$\begin{aligned} v_{ij_{new}} &= \text{round}\left(v_{ij} + f_m \left(v_{ij_{max}} - v_{ij}\right)\right), \text{ if } \ r_1 < 0.5 \\ v_{ij_{new}} &= \text{round}\left(v_{ij} - f_m \left(v_{ij} - v_{ij_{min}}\right)\right), \text{ if } \ r_1 \geq 0.5 \end{aligned} \tag{12}$$

where $f_m = r_2 \exp\left(b \ln\left(k / k_{max}\right)\right)$; $r_1, r_2 \in (0;1)$ are random numbers; $b = 1.05$; *k* is the current iteration and k_{max} is the maximum number of iterations (mating-flights); $v_{ij_{min}}, v_{ij_{max}}$ are the upper and lower limits of gene's values; "round" refers to rounding towards the nearest integer.

In this paper, the best performance, meaning the greatest value of the performance function $F_p = 200/F$, corresponds to the lowest total power consumption within PS, described by the objective function *F* from (11).

HBMOA-M1 input parameters used in this paper are: $N_{in} = 80$ initial potential solutions of the problem, randomly built within admissible ranges of the variables; 2 different sets of runs, the first set with a list of $N_D = 40$ drones, and the 2nd set with $N_D = 20$ drones; spermatheca capacity equal to $N_S = 20$; initial queen speed $V(0) = 1$, with a decay coefficient $\alpha = 0.97$; minimum queen speed $V_{min} = 0.2$; number $N_B = 20$ of new bees; number of mutations $N_M = N_D$ (equal to the number of worker bees); maximum number of iterations $k_{max} = 2000$.

Computations stop either when the maximum number of iterations k_{max} is reached, or before, at iteration $k < k_{max}$, when the imposed precision criterion for queen's performance function is satisfied. In this paper, that criterion is: $F_p \le 1.9$.

4. Numerical results

The computations performed with HBMOA-M1 in this paper correspond to the pumping station (PS) model from Section 2, with the following data:

- two identical centrifugal pumps operating in parallel, with variable speed $n_i \in [n_{min}; n_{max}]$, where $n_{min} = 0.7 n_0 = 1015$ rpm, and $n_{max} = n_0 = 1450$ rpm;
- hydraulic system supplied by PS, with resistance modulus $M = 20000$ s^2/m^5, and static head $H_s = 25$ m, in equation (1);
- pump reduced head curves defined as in (2), for flow rate $Q \in [0; 0.02]$m^3/s, with coefficients: $c_0 = 50$, $c_1 = 0$, $c_2 = 65000$, and hydraulic resistance moduli $M_1 = M_2 = 8000$ s^2/m^5; efficiency of pump *i* operating at $n_i \ne n_0$ as in (3), with coefficients: $c_3 = 0$, $c_4 = 82.5$, and $c_5 = 2750$;
- 4 imposed operating points *A*, meaning 4 pairs $\{Q^*, H^*\}$ of imposed PS head values H^*, and total flow rate values Q^* delivered by PS, as in Table 1.

Some of the computed results are synthesized in Table 1, where upon N_D and imposed $\{Q^*, H^*\}$, presented data are: the run number; the iteration *k* yielding the results; the PS head value H_A and the total flow rate Q_A at *A*; the total power consumption $P = (P_1 + P_2)$ within PS; the speed values n_1 and n_2; the parameters at the individual operation point A_i of each pump ($H_{Ai}, Q_{Ai}, \eta_{Ai}$), where *i* = 1; 2.

Table 1

Numerical results for the studied pumping station model

Run no.	N_D k	Q^* [m^3/s] Q_A [m^3/s]	H^* [m] H_A [m]	P [kW]	n_1 [rpm]; Q_{A1} [m^3/s] H_{A1} [m]; η_{A1} [–]	n_2 [rpm]; Q_{A2} [m^3/s] H_{A2} [m]; η_{A2} [–]
1	40 200	0.02260 0.02263	35.2426 35.2434	13.5271	**1372**; 0.01199 36.3942; 0.60389	**1335**; 0.01064 36.1487; 0.58609
2	20 65	0.02260 0.02263	35.2426 35.2433	13.7025	**1421**; 0.01347 36.6947; 0.61441	**1302**; 0.00916 35.9149; 0.55548
3	40 2000	0.02400 0.02400	35 34.9992	14.3086	**1450**; 0.01433 36.6432; 0.61753	**1308**; 0.00966 35.7464; 0.56822
4	40 2000	0.02600 0.02600	35 34.9994	15.2006	**1444**; 0.01419 36.6099; 0.61719	**1362**; 0.01181 36.1153; 0.60256
5	40 2000	0.02800 0.02800	35 35.0001	16.2886	**1440**; 0.01409 36.5880; 0.61693	**1433**; 0.01391 36.5483; 0.61640

For the pair $\{Q^*,H^*\}$ attached to runs no. 1 and no. 2, the convergence has been achieved for $k << k_{max}$; the best run among those performed with $N_D = 40$ is run no. 1, where the minimum value of power consumption has been achieved; run no. 2, obtained with $N_D = 20$, is the fastest run for the above pair $\{Q^*,H^*\}$. The runs no. 3 to 5 show results obtained after $k = k_{max}$, with $N_D = 40$, for the same H^*, and 3 different Q^* values; none of them succeeded to satisfy restrictions on head, but since the size of head differences is less than 1mm, results are good.

5. Conclusions

A Honey Bees Mating Optimization Algorithm formulation (HBMOA-M1) has been tested on a simple pumping station model, equipped with two variable speed pumps. The optimization process yielded the speed values of each pump, when working in parallel at an imposed pumping station operation point, for the minimal power consumption (objective function of the problem), while satisfying hydraulic constraints with penalty functions for restrictions violation.

Numerical results are promising and justify the use of HBMOA-M1 in further work, for complex problems, i.e. related to pumps schedules optimization for water distribution systems, involving several pumping stations and reservoirs.

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