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

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Funcționarea unei stații de pompare pentru alimentări cu apă variabile în timp poate fi optimizată cu ajutorul Algoritmului de Optimizare bazat pe Înmulțirea Albinelor Melifere (abreviat HBMOA). Algoritmul HBMOA-M1 utilizat în această lucrare este modificat față de cel clasic: soluțiile îmbunătățite la iterația curentă, clasate după regină ca performanță, sunt inserate în lista de trântori în iterația următoare. HBMOA-M1 a fost testat pe un model simplu de stație de pompare, cu pompe cu turație variabilă cuplate în paralel. Prin minimizarea puterii consumate și penalizarea nesatisfacerii restricțiilor hidraulice, procesul de optimizare a furnizat valoarea turației fiecărei pompe pentru atingerea unui punct de funcționare impus.

Pumping station scheduling for variable water supply can be optimised by using the Honey Bees Mating Optimization Algorithm (HBMOA). The algorithm HBMOA-M1 applied in this paper is modified with respect to the classical one: the solutions improved during the current iteration, ranked after the queen as fitness, are inserted within the list of drones for the next iteration. HBMOA-M1 has been tested on a simple pumping station model, equipped with variable speed pumps. The optimization process yielded the speed value of each pump, for parallel pump functioning at a requested operation point, corresponding to the minimization of power consumption, while satisfying hydraulic constraints with penalty functions.

Keywords: Honey Bees Mating Optimization, pumping station scheduling.

1. Introduction

In water distribution systems, the proper scheduling of pump operations can yield to energy cost-savings. Typically, a water supply system is composed of several pumping stations (PS), which supply reservoirs from where water flows towards the distribution network. Such pumping stations are equipped with different pumps that operate in parallel, with variable speed, upon the variable water demand. A pumps schedule is the set of many combinations of pumps operation parameters, variables in time, which must fulfil system restrictions

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regarding the: energy cost, reserved power cost [1], pumps maintenance cost, level variation in reservoirs between imposed limits, water demand pattern etc.

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] and evolutionary algorithms, like Genetic Algorithms – GA [3], Ant Colony Optimization Algorithm – ACOA [4], and Honey Bees Mating Optimization Algorithm – HBMOA [5], were used to find optimal schedules for pumps.

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 [6], 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 [7], [8] 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 [8] 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 used to find optimal schedule for pumps, within a simple pumping station (PS) model, equipped with two identical centrifugal pumps, with variable speed. For such a case, the minimal power consumption (the optimal solution) is attained when operating with both pumps at the *same rotational speed*. That PS model has been selected to test HBMOA-M1 within a major constraint: we imposed to find suboptimal solutions of the problem, defined by pairs of two *different rotational speed* values. The optimization process yielded the speed values of each pump, for parallel pump functioning at requested operation points (given PS heads and flow rates), corresponding to the minimization of power consumption (objective function), while satisfying hydraulic constraints with penalty functions for restrictions violation. We found solutions where the PS total power is slightly greater than the minimal power associated to pumps operating at the same speed.

2. Pumping station model

The pumping station model is based on the following 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 impose here $n_1 > n_2$;

- 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:

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

The pump reduced head curve [9] is defined for $i = 1$ and $i = 2$, as:

$$H_{red\,i} = (n_i/n_0)^2 (c_0 + c_1 Q + c_2 Q^2) - M_i Q^2 . \qquad (2)$$

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:

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

The PS 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 (2), for constant values of $H_{red\,i}$, as:

- if 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 defined as:

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

- if PS head is ranged as $H_s \le H_{PS} \le H_{red2}(0)$, then the delivered $Q_{PS}(H_{PS})$ is:

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

where $d_i = 2\big(c_2 - M_i(n_0/n_i)^2\big)\big/c_1$, for $i = 1; 2$. The operating point A of the PS is defined at the intersection between the PS head curve $H_{PS}(Q_{PS})$, and the system head curve $H_{hsys}(Q_{hsys})$; so at the point A, we obtain: $Q_A = Q_{PS}\big|_A \equiv Q_{hsys}\big|_A$ and $H_A = H_{PS}\big|_A \equiv H_{hsys}\big|_A$. The value of pumping station head in A is obtained by solving the equations $f_a(H_A) = 0$ or $f_b(H_A) = 0$, 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 $H_{red_2}(0) \le H_A \le H_{red_1}(0)$

$$f_b = \sum_{i=1}^{2} \frac{-1 + \sqrt{1 - 2d_i(c_0 - H_A(n_0/n_i)^2)/c_1}}{d_i} - \sqrt{\frac{(H_A - H_s)}{M}} = 0. \tag{7}$$
if $H_s \le H_A \le H_{red_2}(0)$

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 $[n_{min}; n_{max}]$. Equations (6) and (7) are solved as:

$$\begin{cases} \text{if } f_a\big(H_{red_1}(0)\big) \cdot f_a\big(H_{red_2}(0)\big) < 0 \Rightarrow \text{eq.(6) is solved} \\ \text{if } f_b\big(H_{red_2}(0)\big) \cdot f_b(H_s) < 0 \quad\quad \Rightarrow \text{eq.(7) is solved} \end{cases}. \tag{8}$$

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. The power P_i ($i = 1; 2$) is the output mechanical power of electrical motor driving the pump.

A simple objective function F consists of minimizing the pumping station total power consumption P, as $F = \min\{P\}$, while satisfying hydraulic restrictions sets defined by R_a or R_b:

$$R_a = \begin{cases} 0.7 n_0 \leq n_i \leq n_0 \\ Q_A = \sum_i Q_{Ai} = Q^* \text{ (requested total flow rate)} \\ H_A \geq H^* \qquad \text{(minimum PS head)} \end{cases}$$

(9)

$$R_b = \begin{cases} 0.7 n_0 \leq n_i \leq n_0 \\ H_A = H^* \qquad \text{(requested PS head)} \\ Q_A = \sum_i Q_{Ai} \geq Q^* \text{ (minimum total flow rate)} \end{cases}$$

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 here consists of minimizing the PS total power consumption (in watt), while satisfying hydraulic constraints (9) with penalty functions, as:

$$F = \min\left\{10^{-2} \sum_i P_i + p_1 |Q^* - Q_A| + p_2 |H^* - H_A|\right\}$$

$$\text{where } p_1 = \begin{cases} 10^6 & \text{if } Q_A < Q^* \\ 0 & \text{if } Q_A \geq Q^* \end{cases}, \text{and } p_2 = \begin{cases} 10^5 & \text{if } H_A < H^* \\ 0 & \text{if } H_A \geq H^* \end{cases}$$

(10)

where p_1 and p_2 are penalty coefficients for restrictions violation.

The performance function F_p used in HBMOA-M1 formulation is: $F_p = 200/F$. The best performance (greatest F_p value) corresponds to the lowest total power consumption, described by the objective function F from (10).

3. Honey Bees Mating Optimization Algorithm (HBMOA) parameters

HBMOA has been fully described in Popa & Georgescu [8]. We present here only data attached to the studied optimization problem, within HBMOA-M1 formulation, to determine the optimal schedule for pumps operating in parallel within a pumping station. In this paper, a solution (honey bee) has a number of unknowns (genes) equal to the total number of pump speed values n_i (where $i = 1; 2$ for the studied simple PS model, or $i = 1 \div N$ if the problem is generalized to a PS operating with N pumps, with different head curves). There is a difference between the HBMOA steps described in [8], and the present paper: we used here a different non-uniform mutation operator, namely the value v_{ij} of the gene j (one variable from bee's genome), selected for mutation, is modified to:

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

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. HBMOA-M1 input parameters used here 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 second set with $N_D = 20$ drones; spermatheca capacity $N_S = 20$; initial queen speed $V(0) = 1$; 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 $k = k_{max}$, or at $k < k_{max}$, when the precision criterion for queen's performance ($F_p \leq 1.9$) is satisfied.

4. Numerical results

The computations performed using HBMOA-M1 correspond to the pumping station 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 $M = 20000 \, \text{s}^2/\text{m}^5$, and static head $H_s = 25 \, \text{m}$, in equation (1);

- pump reduced head curves defined as in (2), for flow rate $Q \in [0; 0.02] \, \text{m}^3/\text{s}$, with coefficients: $c_0 = 50$, $c_1 = 2.22 \cdot 10^{-16}$, $c_2 = 65000$, and hydraulic resistance moduli $M_1 = M_2 = 8000 \, \text{s}^2/\text{m}^5$; efficiency of pump i operating at $n_i \neq n_0$ as in (3), with coefficients: $c_3 = 0$, $c_4 = 82.5$, and $c_5 = 2750$;

- 4 requested operating points A, meaning 4 pairs $\{Q^*, H^*\}$ of imposed total flow rate values Q^* delivered by PS, and PS head values H^*, as in Table 1.

Table 1

Numerical results for the studied pumping station model: suboptimal solutions obtained using HBMOA-M1 by imposing $n_1 \neq n_2$, compared with optimal solutions attached to $n_1 = n_2$

Run no./ iter. k	Imposed versus attained values		Suboptimal solutions $n_1 \neq n_2$ using HBMOA-M1			Solutions $n_1 = n_2$
	Q^* [m³/s] Q_A [m³/s]	H^* [m] H_A [m]	P [kW]	n_1 [rpm]; Q_{A1} [m³/s] H_{A1} [m]; η_{A1} [−]	n_2 [rpm]; Q_{A2} [m³/s] H_{A2} [m]; η_{A2} [−]	n_1 [rpm] P [kW]
1/ 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	**1352.2** 13.4925
2/ 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	**1352.2** 13.4925
3/ 2000	0.02400 0.02400	35 34.9992	14.3086	**1450**; 0.01433 36.6432; 0.61753	**1308**; 0.00966 35.7464; 0.56822	**1367.6** 14.0808
4/ 2000	0.02600 0.02600	35 34.9994	15.2006	**1444**; 0.01419 36.6099; 0.61719	**1362**; 0.01181 36.1153; 0.60256	**1399.6** 15.1417
5/ 2000	0.02800 0.02800	35 35.0001	16.2886	**1440**; 0.01409 36.5880; 0.61693	**1433**; 0.01391 36.5483; 0.61640	**1436.5** 16.2889

In Table 1, run no.2 is performed for $N_D = 20$, while $N_D = 40$ for the others runs. Upon the requested $\{Q^*, H^*\}$ pairs, presented data are: the run number; the iteration k yielding the results; the total flow rate Q_A and the PS head value H_A attained at A; the minimal total power consumption $P = (P_1 + P_2)$ obtained using HBMOA-M1 when operating with $n_1 \neq n_2$, together with the rotational speed values n_1 and n_2 (where $n_1 > n_2$) and the parameters at the individual operation point A_i of each pump ($H_{A_i}, Q_{A_i}, \eta_{A_i}$), for $i = 1; 2$. Those results are compared in Table 1 with the minimal total power consumption P when operating with $n_1 = n_2$, where the equal values of the rotational speed were obtained by solving equation (5) for $Q_{PS} \equiv Q^*$ and $H_{PS} \equiv H^*$. The suboptimal solutions obtained

using HBMOA-M1 by imposing $n_1 \neq n_2$ are slightly greater than the optimal solutions attached to the condition $n_1 = n_2$ (the average relative error is of 0.75%).

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 insignificant, results are good.

5. Conclusions

A modified Honey Bees Mating Optimization Algorithm (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, while satisfying hydraulic constraints with penalty functions for restrictions violation. The results justify using further HBMOA-M1, to find optimal schedule for pumps for water supply system consisting of several pumping stations and variable level reservoirs, each PS equipped with its own type of pumps; for such complex case, the algorithm can found the combination of all pumps speed values, leading to overall minimal power consumption.

R E F E R E N C E S

[1]. *G. McCormick and R. S. Powell*, "Optimal Pump Scheduling in Water Supply Systems with Maximum Demand Charges", J. Water Res. Pl.-ASCE, **vol. 129**, no. 5, 2003, pp. 372-379
[2]. *F. E. Goldman and L. W. Mays*, "The application of Simulated Annealing to the optimal operation of water systems", in WRPMD'1999, ASCE, ed. E. M. Wilson, 1999, ch. 9D198
[3]. *M. Moradi-Jalal, S. I. Rodin and M. A. Mariño*, "Use of genetic algorithm in optimization of irrigation pumping stations", in J. Irrig. Drain. E-ASCE, **vol. 130**(5), 2004, pp. 357-365
[4]. *M. López-Ibáñez, T. D. Prasad and B. Paechter*, "Ant Colony Optimization for optimal control of pumps in water distribution networks", J.W.Res.Pl.-ASCE, **134**(4),2008, 337-346
[5]. *O. B. Haddad and M. A. Mariño*, "Dynamic penalty function as a strategy in solving water resources combinatorial optimization problems with honey-bee mating optimization (HBMO) algorithm", in J. Hydroinform., **vol. 9**, no. 3, 2007, pp. 233–250
[6]. *O. B. Haddad, A. Afshar and M. A. Mariño*, "HBMO in Engineering optimization", in Proc. IWTC9 2005, Sharm El-Sheikh, Egypt, 2005, pp. 1053-1063
[7]. *T. Niknam, J. Olamaie and R. Khorshidi*, "A hybrid algorithm based on HBMO and Fuzzy Set for multi-objective distribution feeder reconfiguration", in WASJ, **4**(2), 2008, 308-315
[8]. *R. Popa and Sanda-Carmen Georgescu*, "Water distribution networks optimal design using the Honey Bees Mating Optimization Algorithm", Proc. 4th CIEM, Bucharest, 2009, S6_10
[9]. *A.-M. Georgescu and Sanda-Carmen Georgescu*, Hidraulica rețelelor de conducte și mașini hidraulice (Hydraulic networks and hydraulic machineries), Ed. Printech, Bucharest, 2007.