Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 162 (2016) 494 – 502

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Efficient & Sustainable Water Systems Management toward Worth Living Development, 2nd EWaS 2016

An application of the Harmony-Search Multi-Objective (HSMO) optimization algorithm for the solution of pump scheduling problem

Francesco De Paola[a,*], Nicola Fontana[b], Maurizio Giugni[a], Gustavo Marini[b], Francesco Pugliese[a]

[a]*University of Naples, Via Claudio 21, 80125 Naples, Italy*
[b]University of Sannio, Piazza Roma 21, 82100 Benevento, Italy

Abstract

In hydraulic systems, water is often pumped to reach higher elevations, so as to ensure the minimum required pressure and guarantee adequate service level. However, pumps cannot be instantly activated and people do not consume the resource in uniform mode throughout the day. To avoid direct pumping, water can be stored in tanks at a higher elevation, so that it can be supplied whenever there is a higher demand. Because of the significant costs required for pumping, energy-saving in water supply systems is one of the most challenging issues to ensure optimal management of water systems. Careful scheduling of pumping operations may lead not only to energy savings, but alsoto prevent damages, as consequence of reduction of operation times and switches. By means of computer simulation, an optimal schedule of pumps can be achieved using optimization algorithms. In this paper, a harmony-search multi-objective (HSMO) optimization approach is adapted to the pump scheduling problem. The model interfaces with the popular hydraulic solver, EPANET 2.0, to check the hydraulic constraints and to evaluate the performances of the selected schedules. Penalties are introduced in the objective function in case of violation of the hydraulic constraints. The model is applied to a case study, showing that the results are comparable with those of competitive meta-heuristic algorithms (e.g. Genetic Algorithms) and pointing out the suitability of the HSMO algorithm for pumping optimization.

Peer-review under responsibility of the organizing committee of the EWaS2 International Conference on Efficient & Sustainable Water Systems Management toward Worth Living Development

* Corresponding author. Tel.: +390817689820; fax: +390817689820.
E-mail address: depaola@unina.it

Peer-review under responsibility of the organizing committee of the EWaS2 International Conference on Efficient & Sustainable Water Systems Management toward Worth Living Development
doi:10.1016/j.proeng.2016.11.093

Keywords: Water Networks; Optimization techniques; Pump scheduling; Meta-heuristic algorithms.

1. Introduction

Over the last decades, the optimization of water systems represented a issue of greatest interest, also because of the economic and social impact on society. To this aim, technicians are called to produce solutions which allow saving time and money, often using optimization techniques. Various mathematical models, such as linear, nonlinear and dynamic programmings are applied to optimize water systems. However, the increase of the number of variables in optimization algorithms exponentially increase the number of function evaluations, thus requiring huge memory space in computer. These features, unfortunately, are limiting their application to a variety of water system optimization problems.

The computational limits of mathematical programming algorithm addressed scientists to refer on natural inspired algorithm such as Genetic Algorithm [1, 2], Simulated Annealing [3] and Tabu Search [4, 5] to solve optimization problems for water systems, by combining, as common factor, rules and randomness to reproduce natural phenomena.

In the past two decades, the above mentioned algorithms were broadly applied to solve several water system optimization problems. These algorithms successfully overcome several deficiencies of conventional mathematical optimization algorithms. However, a recently new nature-inspired algorithm based on analogies with natural phenomena still remains to be explored. For example Geem et al. [6] developed a Harmony Search (HS) algorithm which numerically reproduces the musician improvisation process for searching a perfect musical harmony.

Nomenclature

HSMO	Harmony Search Multi-Objective
C_T	Total energy cost for a 24-h period
TN_{SW}	Total number of pump switches in 24-h period
t	Hourly time step
C(t)	Unit cost for time step t
E(t)	Consumed energy at time step t
$Q_p(t)$	Pump flow at time step t
H(t)	Water tank level at time step t
$N_{sw}(t)$	Number of pump switches at time step t
SW	Number of switches allowed per pump
N^P	Total number of pumps
HM	Harmony Memory
HMCR	Harmony Memory Considering Rate
PAR	Pitch Adjusting Rate
HMS	Harmony Memory Size
r_1	Random real number
x’	Harmony Memory vector
Pr	Procedure to generate random number

The harmony in music is analogous to the solution vector and the behavior of musician's improvisation corresponds to local and global search schemes in optimization techniques. These behaviors were successfully translated in various optimization applications [7-14].

In the present paper, a Harmony-Search Multi-Objective (HSMO) optimization approach is applied to the pump scheduling problem solving. The model interfaces with the popular hydraulic solver EPANET 2.0 [15], to check the hydraulic constraints and to evaluate the performances of the selected schedules. Penalties are introduced in the objective function in case of violation of the hydraulic constraints.

The model is applied to the well known case study Anytown [16], showing that the results are comparable with those of competitive meta-heuristic algorithms (e.g. Genetic Algorithms) and pointing out the suitability of the HSMO algorithm for pumping optimization.

2. Methodology

Existing meta-heuristic algorithms are based on ideas found in the paradigm of natural or artificial phenomena. These include the biological evolutionary process in the Genetic Algorithms [1, 2], the physical annealing process in Simulated Annealing [3] and animal's behavior in Tabu Search [4, 5]. Geem et al. [6] developed a Harmony Search (HS) meta-heuristic optimization algorithm that is conceptualized from the musical process of searching for a "perfect state" of harmony, such as jazz improvisation. The HS algorithm was applied to various science and engineering optimization problems that include: Real-world applications [7-8],Computer science, Electrical, Civil and Mechanical engineering problems [9-14]. In addition to the above-mentioned various applications, the HS algorithm also possesses various algorithm structures, applicable to so many different issues.

Water pump switching problem consists of supplying water in a hydraulic system, by minimizing the energy cost and satisfying, at the same time, the required pressure in the system. Pump scheduling process, in a Water Distribution Network, represents the choice of which available pumps have to be activated in the different daily time steps.

Several researches are focused on the pump scheduling optimization, with the aim of minimizing the marginal cost of supplying water, in compliance with the physical and operational constraints of the system [17-22]. Further problems are represented by the evaluation of optimal functioning, as function of electricity tariff which consistently varies into a typical operating cycle and by the hydraulic behavior which results highly nonlinear [23]. These issues cause a complex computer modeling, computationally demanding and a time consuming process [24].

In this field, in the present paper the pump scheduling problem is treated as a two-objective optimization problem, having as objectives the minimisation of energy costs and of pump switches:

$$MinC_T = \sum_{t=1}^{24} C(t) \cdot E(t) \tag{1}$$

$$MinC_T = \sum_{t=1}^{24} N_{SW}(t) \tag{2}$$

with C_T the total energy costs for a 24-hours period, TN_{SW} the total number of pump switches in 24-h period, t the hourly time step, $C(t)$ the unit cost during time step t, $E(t)$ the energy consumed in the time step t (function of pump flow $Q_p(t)$ and tanks water level, $H(t)$ and $N_{SW}(t)$ the number of pump switches during the time t. A pump switch is defined as the action of turning on or off a pump that was not or operating during the previous time step. Frequently switching of a pump can cause wear and tear. However, in greater detail, our goal is limiting the number of switches of each pump (TN_{sw}^P) and consequently the total number of switches TN_{sw}:

$$TN_{SW} = \sum_{p=1}^{N_p} TN_{SW}^p \tag{3}$$

Because by limiting TN_{sw} a schedule may still contain a pump with an excessive number of switches, the objective is also applied to TN_{sw}^P. Thus, to strictly limit the number of switches per pump to a specified value, the following constraint is considered:

$$TN_{SW}^P \le SW, \quad \forall p \in \{1,..,N^p\} \tag{4}$$

where SW is a constant to be specified (in the present study equal to 6) that represents the number of switches allowed per pump during the scheduling period and N^p is the total number of pumps.

The main constraint is represented by the water level in the tanks, which has to be comprised between the allowable minimum H_{min} and maximum H_{max} storage head, which depends on the tank water level $H(t-1)$ during the previous time step and on the pump station flow $Q_P(t)$ at the same time step:

$$H_{\min} \leq H(t) \leq H_{\max} \tag{5}$$

Further constraint regards the combination of deliverable flows by pumps, which is function of the pump characteristics and of the tank water level:

$$0 \leq Q_p(t) \leq Q_{p,\max}(t) \tag{6}$$

In addition, a third constraint ensures that the initial water level is reached or exceeded in the tank at the end of the optimization period:

$$H(t=24) \geq H(t=0) \tag{7}$$

The above constraints are the most frequently used constraints [20]. Additional constraints, such as limits on source flows or velocity constraints, may be incorporated to the problem formulation depending on particular requisites of a network. For example, when a hydraulic simulator is used to evaluate pump schedules, the simulator may issue warnings for specific undesirable situations. Such warnings indicate that the schedule is problematic and should not be considered a feasible solution to the problem. Therefore, an additional constraint could be added that requires feasible solutions to generate no simulation warnings.

The procedure of the HS multi-objective algorithm consists of 5 Steps [6]:

- *Step 1*: Initialization of optimization problem and HS algorithm parameters;
- *Step 2:* Initialization of Harmony Memory (HM);
- *Step 3:* Improvisation of a new harmony from HM;
- *Step 4:* Updating HM;
- *Step 5*: Checking the stopping criterion.

- *Step 1:* the algorithm parameters required to solve the optimization problem of Equations (1) and (2), are specified in this step: Harmony Memory Considering Rate (HMCR), Pitch Adjusting Rate (PAR), Harmony Memory Size (HMS: number of solution vectors) and termination criterion (number of improvisations or rather number of function evaluations). HMCR and PAR parameters are used to improve solution vectors and they are defined in Step 3. In multi-objective formulation, a Pareto set of solution is searched. Pareto domination assumes that solution A dominates solution B, if and only if:

$$\forall i \in \{1, 2, ..., N\}, f_i(A) \leq f_i(B) \text{ and } \exists i \in \{1, 2, ..., N\}, f_i(A) < f_i(B) \tag{8}$$

  Solution A belongs to the Pareto optimal set if there is not any solution B which dominates A; therefore Pareto optimal set collects all Pareto optimal solutions and it is graphically represented, in the objective space, by the Pareto front. In this paper, an archive set (Harmony Matrix, HM) is used to record the non-dominated solutions during the iterations and, proceeding the evolutions, if one new solution dominates one or more solutions in HM, it will replace the dominated solutions in HM.
- Step 2: Harmony Memory (HM) (matrix shown in Equation 9) is filled with many randomly generated solution vectors as the HMS.

$$HM = \begin{bmatrix} x_1^1 & \cdots & x_N^1 \\ \vdots & \vdots & \vdots \\ x_1^{HMS} & \cdots & x_1^{HMS} \end{bmatrix} \begin{matrix} \rightarrow & f(x^1) \\ \vdots & \vdots \\ \rightarrow & f(x^{HMS}) \end{matrix} \quad (9)$$

- *Step 3:* A new harmony vector, $\boldsymbol{x'}=(x'_1, x'_2,..., x'_N)$ is generated, based on three rules: Memory Considerations, Pitch Adjustments, and Randomization. For instance, in the classical formulation of the Harmony Search, the value of the first decision variable (x'_1) can be chosen from any value in the specified HM range ($x_1^1 \sim x_1^{HMS}$). However, there is also a possibility that totally random value can be chosen for the decision variable x'_i:

$$x'_i = \begin{cases} x'_i \in \{x_i^1, x_i^2, ..., x_i^{HMS}\} & \text{with probability } HMCR \\ x'_i \in \mathbf{X}_i & \text{with probability } (1-HMCR) \end{cases} \quad (10)$$

  where HMCR (between 0 and 1) is the probability of choosing one value from the historical values stored in the HM, and the complement (1-HMCR) is the probability of random feasible value, not limited to those stored in the HM. Values of the other decision variables (x'_2 ,..., x'_N) can be chosen in the same manner. After the memory considering operation, pitch adjusting operation follows. The pitch adjusting operation, in the classical approach, is performed only for the values which have been chosen from the HM. This operation uses the PAR parameter that sets the rate of moving to neighboring values for the originally chosen value from the HM. For the pump scheduling problem, the pitch adjusting operation is not performed because candidate values for each decision variable are only 0 or 1 [7]. A variant of the original method is also proposed in the present paper for the choice of the new Harmony Memory vector **x**'. For each decision variable, the following procedure is followed:

$$x'_i = \begin{cases} x'_i = x_i^1 & \text{if } \mathrm{r}_1 < HMCR \\ R & else \end{cases} \quad (11)$$

  in which r_1 is a random real number between 0 and 1, while R=*INT*(*Pr*+ε), being *Pr* a procedure to generate random real numbers, uniformly distributed between 0 and 1, and ε a tuning factor used to speed up the process. The value of ε was set to 0.65 in this paper. *INT* refers to the function that returns the integer part of the real number (0 or 1 respectively). In the classical approach, after the memory considering operation, pitch adjusting operation follows. The pitch adjusting operation is performed only for the values which were chosen from the HM. This operation uses the PAR parameter that sets the rate of moving to neighboring values for the originally chosen value from the HM. For the pump scheduling, however, the pitch adjusting operation is not considered because candidate values for each decision variable are only 0 or 1.
- *Step 4:* If the new harmony vector $x' = (x'_1, x'_2 ,...,x'_N)$ is better than the worst harmony in the HM, in terms of objective function value, the new harmony is included into the HM and consequently the existing worst harmony is excluded from it.
- *Step 5:* The computations are terminated when the termination criterion (number of function evaluations in this study) is satisfied. If not, Steps 3 and 4 are repeated.

3. Results

The "Anytown" network example (Fig. 1) proposed by Pasha and Lansey [25] has been used in this study. The network is composed by 37 pipes, 19 nodes, 1 tank (node 21) and 1 source (node 20) with 4 pumps installed at the pump station at the source (ID numbers 38, 39, 40, 41). The tank elevation and diameter are 65.53 m and 12.20 m, respectively. Due to complex, nonlinear behavior of the system, EPANET 2.0 software [15] is used to assess the response of the system at changing pump operation and to verify all the hydraulic constraints are satisfied. If conditions (5) and (7) are not satisfied, the software automatically sums the total cost CT a quantity (9999), so as to rapidly exclude ineligible solutions. If condition (6) is not respected (indicated into the EPANET 2.0 warnings report), the software goes to the initial phase of the algorithm in which starting solutions are achieved. Therefore every iteration produces feasible solutions (with respect to condition (6)), without warning. Both hydraulic time step and pattern time step are set to 1 hour. Minimum and maximum tank heads are set to 67.67 m and 76.20 m, respectively. Hourly demand factors ranged from 0.4 to 1.2 (Fig. 2), whereas base demand is doubled from the Anytown test case in order to allow longer pump operation and tank storage, defining a total inflow between 161.51 lps and 484.53 lps. Finally, an electricity tariff with a price of 0.0244 \$/kWh between 0:00 - 7:00 and 0.1194 \$/kWh between 8:00 to 24:00 was considered for simulations.

In Fig. 3, the characteristics curves of the installed pumps are given. As there are 4 fixed speed pumps in the system, the total number of possible pump combinations is $2^4 = 16$ during each hour of the day, consequently the total search space is 7.92×10^{28}.

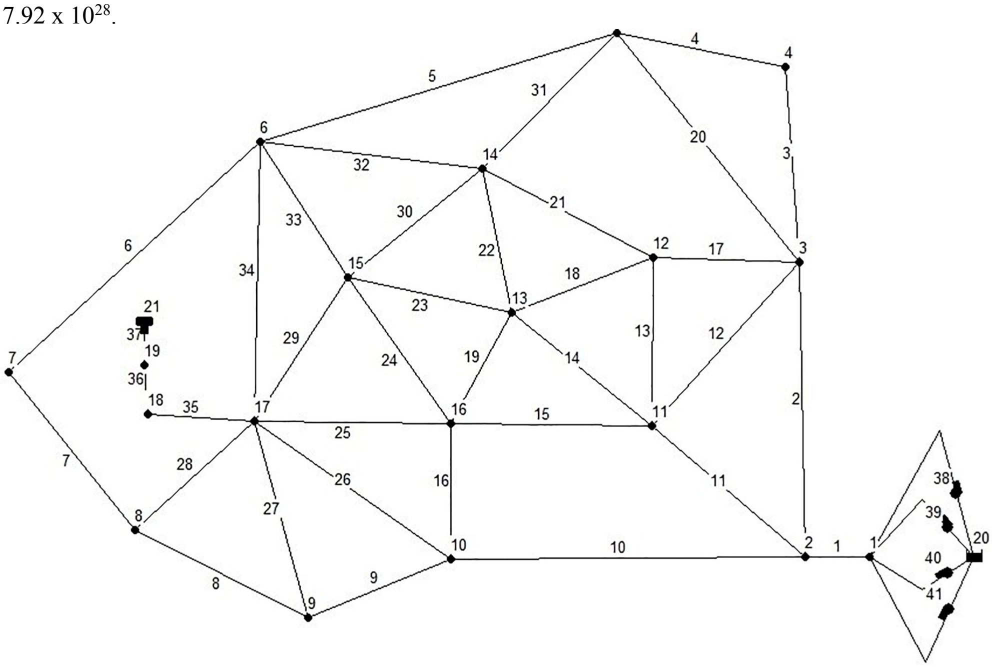

Fig. 1. Anytown water distribution network example [25].

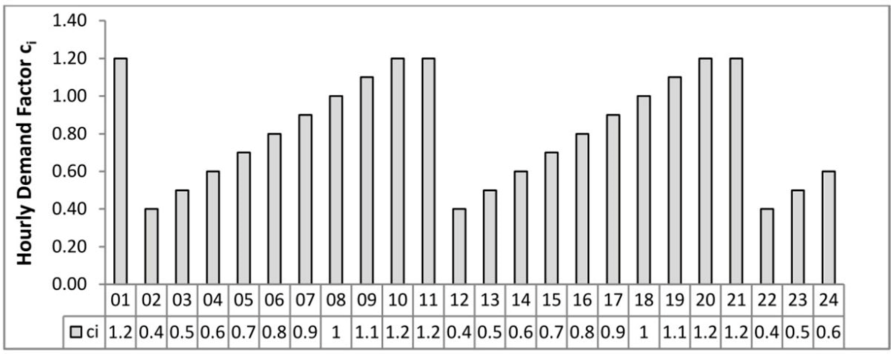

Fig. 2. Daily pattern of hourly demand factors.

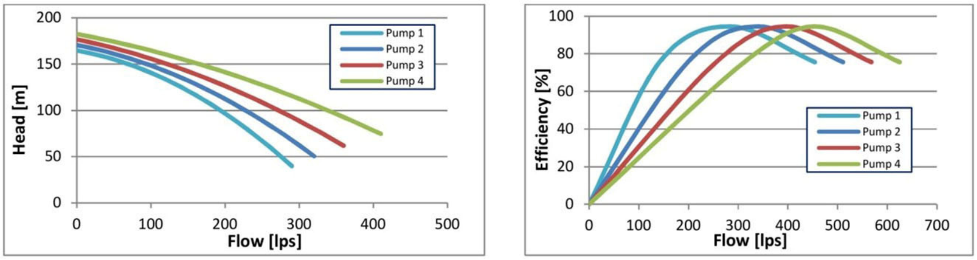

Fig. 3. Characteristic curves of 4 pumps in Anytown: (a) Flow-Head; (b) Flow-Efficiency.

The proposed HSMO leads to the results showed in Table 1 and Figs. 4-6. In particular, the values of the two objective functions are equal to C_T=871.25 \$ and TN_{SW}=14. The best solution (in terms of costs minimization) shows (Fig. 4) that one pump (Pump 3 - ID 40) is always switched off and, at any time step, a maximum of 2 pumps are switched on. This circumstance is also confirmed by others solution in Pareto front, so that Pump 3 can operate as a supply pump. From Fig. 3 it's in fact visible how, for lower values of the considered inflow range, Pump 3 efficiency results lower than Pumps 1 and 2 ones while, for higher values, Pump 4 efficiency is higher, determining the exclusion of Pump 3 activation in the best solution. Fig. 5 shows the daily cost variation, whereas in Fig. 6 the head tank variation is plotted. Such plot also shows the respect of the constraints (5) and (7).

Table 1. Anytown water distribution pump scheduling HSMO results.

Pump ID	Daily Percent Utilization *(%)*	Average Efficiency *(%)*	Number of Switches *(-)*	Electric Energy *(kWh/m³)*	Average Power *(kW)*	Peak Power *(kW)*	Energy Cost *($/day)*
38 (Pump 1)	75.00	82.48	6	0.33	223.79	236.60	370.65
39 (Pump 2)	37.50	75.69	4	0.39	288.50	305.54	174.56
40 (Pump 3)	0	0	0	0	0	0	0
41 (Pump 4)	29.17	76.21	4	0.38	440.83	489.58	326.05
Total			**14**				**871.25**

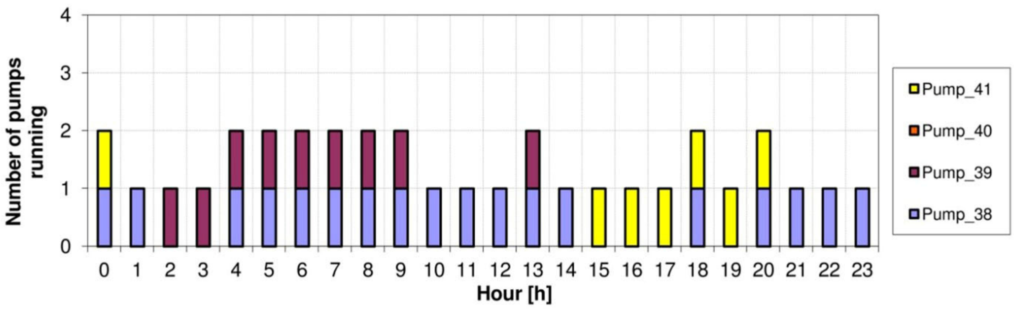

Fig. 4. Number of pump running at any hour.

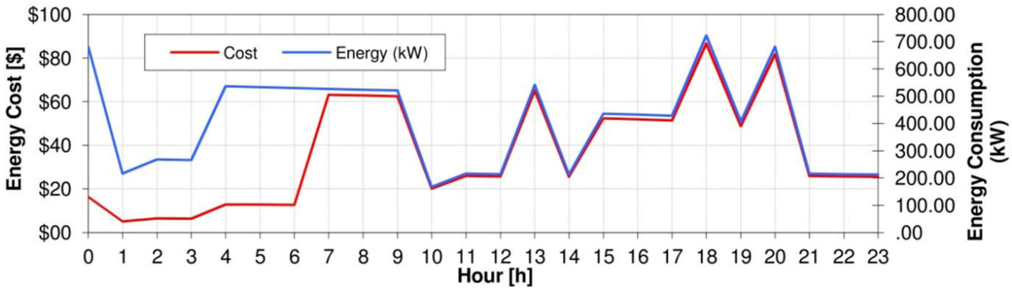

Fig. 5. Energy Consumption and related Energy Cost per hour (daily distribution).

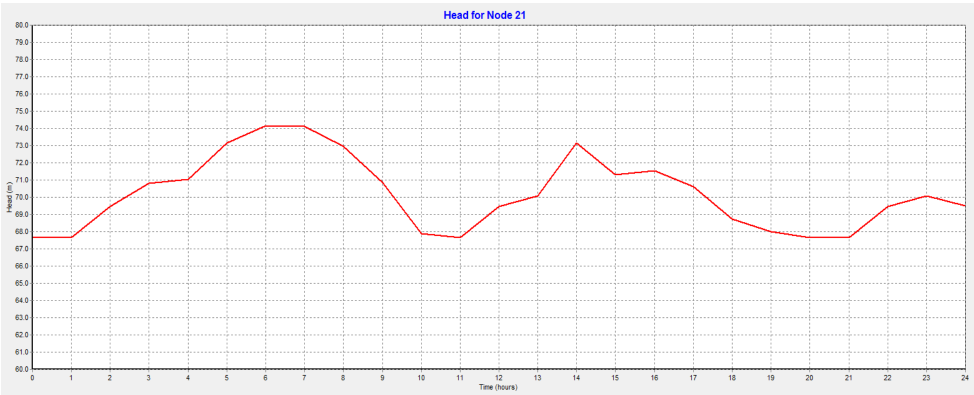

Fig. 6. Tank (ID 21) hourly head variation.

Finally, in Fig. 7 the representation of the Pareto is given. Cost reduces by about 60% with 4 daily switches, whereas a reduction of about 80% can be achieved by considering 14 switches per day.

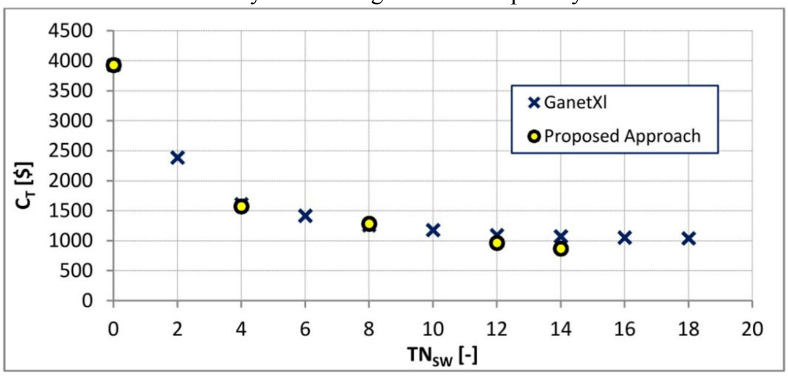

Fig. 7. Pareto set solutions for the HSMO procedure.

The results obtained by GanetXl [20], which is implemented using genetic algorithm technique, are very close to the proposed approach, showing a cost reduction of about 58% with only 4 switches per day, and 75%, with 18 switches and 2000 generations (with very similar time computations 5-10').

4. Conclusions

Optimizing pumping operation in hydraulic systems guarantees both economical and environmental savings. In complex systems, due to the difficulty of assessing the best solution by means of analytical methods, meta-heuristic algorithms represent an effective solution to achieve good solutions in reasonable times. In the present work a Harmony-Search Multi-Objective optimization approach coupled to the hydraulic solver EPANET 2.0 was proposed for optimal pump scheduling.

The algorithm was applied to the well-known Anytown Water Distribution Network in which four pumps are installed. A two-hourly pump tariff was taken into account, and constraints on both water level in tanks and flows supplied by pumps. The fitness function expressed the minimization of energy costs and the number of pump switches per day. Obtained solutions show that one pump is always switched off and a maximum of 2 pumps are simultaneously switched on. The number of total switches per day ranges between 4, with a cost reduction of about 60%, and 14, with a saving of about 80%.

References

[1] K.A. De Jong, An analysis of the behaviour of a class of genetic adaptive systems, Ph.D. Thesis, University of Michigan Ann Arbor, 1975.
[2] D.E. Goldberg, Genetic Algorithms in search, in: Addison-Wesley Longman Publishing Co. Optimization and Machine Learning., Boston, 1989.
[3] S. Kirkpatrick, C.D. Gelatt JR, M.P. Vecchi, Optimization by Simulated Annealing, Science 220 (1983) 671–680.
[4] F. Glover, Tabu Search - Part 1, J. Comput. 1 (1989) 190–206.
[5] F. Glover, Tabu Search - Part 2, J. Comput. 2 (1990) 4–32.
[6] Z.W. Geem, J.H.Kim, GV. Loganathan, A new heuristic optimization algorithm: Harmony Search, Simul. 76 (2001) 60-68.
[7] Z.W. Geem, Harmony Search algorithm for solving Sudoku, Lect. Notes Comput. Sci. 4692 (2007) 371-378.
[8] Z.W. Geem, C.L. Tseng, Y. Park, Harmony Search for generalized orienteering problem: best touring in China, Lect. Notes Comput. Sci. 3612 (2005) 741-750.
[9] F. De Paola, E. Galdiero, M. Giugni, F. Pugliese, Sustainable development of storm-water systems in African cities considering climate change, Procedia Eng. 119 (2015) 1181-1191.
[10] F. De Paola, M. Giugni, E. Galdiero, A jazz based approach for optimal setting of pressure reducing valves in water distribution networks, Eng. Opt. 48 (2015) 727-739.
[11] Z.W. Geem, Optimal scheduling of multiple dam system using Harmony Search algorithm, Lect. Notes Comput. Sci. 4507 (2007) 316-323.
[12] M.T. Ayvaz, Simultaneous determination of aquifer parameters and zone structures with fuzzy C-means clustering and meta-heuristic Harmony Search algorithm, Adv. Water Resour. 30 (2007) 2326-2338.
[13] Z.W. Geem, J.C. Williams. Ecological optimization using Harmony Search, Proc. Am Conf. Appl. Math., Harvard University, 2008, pp. 24–26.
[14] Z.W. Geem, K.S. Lee, Y. Park, Application of Harmony Search to vehicle routing, Am. J. App. Sci. 2 (2005) 1552-155.
[15] L.A. Rossmann, EPANET 2 User's Manual, United States Environmental Protection Agency, Cincinnati, 2000.
[16] T.M. Walski, E.D. Brill, J. Gessler, I.C. Goulter, R.M. Jeppson, K. Lansey, H.L. Lee, J.C. Liebman, L. Mays, D.R. Morgan, L. Ormsbe, Battle of the network models: epilogue, J. Water Resour. Plann. Manage. ASCE 113 (1987) 191-203.
[17] P.W. Jowitt, G. Germanopoulos, Optimal pump scheduling in water-supply networks, J. Water Resour. Plann. Manage. ASCE 118 (1992) 406-422.
[18] G. Mackle, D.A. Savic, G.A. Walters, Application of Genetic Algorithms to pump scheduling for water supply, Proc. 1st Intern. Conf. Genetic Algorithms in Engineering Systems: Innovations and Applications (GALESIA), 1995, pp. 400-405.
[19] D.A. Savic, G.A. Walters, M. Schwab, Multiobjective Genetic Algorithm for pump scheduling in water supply, Proc. Evolutionary Computing Workshop, Manchester, 1997, pp. 227-236.
[20] D.A. Savic, J. Bicik, M.S. Morley, A DSS Generator for Multiobjective Optimization of Spreadsheet Based Models, Environm. Model. Soft. 26 (2011) 551-561.
[21] A. Ostfeld, A. Tubaltzev, Ant colony optimization for least-cost design and operation of pumping Water Distribution Systems, J. Water Resour. Plann. Manage. ASCE 134 (2008) 107-118.
[22] M. Lopez-Ibáñez, T.D. Prasad, B. Peachter, Ant colony optimization for optimal control of pumps in Water Distribution Networks, J. Water Resour. Plann. Manage. ASCE 134 (2008) 337-346.
[23] C. Biscos, M. Mulholland, M.V. Le Lann, C.A. Buckley, C.J. Brouckaert, Optimal operation of water distribution networks by predictive control using MINLP, Water SA 29 (2004) 393-404.
[24] J.E. Van Zyl, D.A. Savic, G.A. Walters, Operational optimization of water distribution systems using a Hybrid Genetic algorithm, J. Water Resour. Plann. Manage. ASCE 130 (2004) 160-170.
[25] M.F.K. Pasha, K. Lansey, Optimal pump scheduling by linear programming, Proc. World Environ. Water Res. Congress, Kansas City, 2009, pp. 395-404.