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Soccer league competition algorithm: A novel meta-heuristic algorithm for optimal design of water distribution networks

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ABSTRACT

Water distribution networks are one of the most important elements in the urban infrastructure system and require huge investment for construction. Optimal design of water systems is classified as a large combinatorial discrete non-linear optimization problem. The main concern associated with optimization of water distribution networks is related to the nonlinearity of discharge-head loss equation, availability of the discrete nature of pipe sizes, and constraints, such as conservation of mass and energy equations. This paper introduces an efficient technique, entitled Soccer League Competition (SLC) algorithm, which yields optimal solutions for design of water distribution networks. Fundamental theories of the method are inspired from soccer leagues and based on the competitions among teams and players. Like other meta-heuristic methods, the proposed technique starts with an initial population. Population individuals (players) are in two types: fixed players and substitutes that all together form some teams. The competition among teams to take the possession of the top ranked positions in the league table and the internal competitions between players in each team for personal improvements are used for simulation purpose and convergence of the population individuals to the global optimum. Results of applying the proposed algorithm in three benchmark pipe networks show that SLC converges to the global optimum more reliably and rapidly in comparison with other meta-heuristic methods.

1. Introduction

The fundamental goal of water distribution network optimization is to minimize the costs while satisfying the performance and hydraulic constraints required by the design codes and specifications. This involves determining the commercial diameter for each pipe in the network while satisfying the minimum head pressure at each node. The optimal design cost is the minimum option out of numerous possibilities.

The nonlinear relationships between pipe discharges and head loss along with the presence of pipe diameters in design optimization makes this task highly challenging. Over the last two decades many evolutionary optimization techniques have been successfully applied to water network optimal design, such as genetic algorithms [1–4]; simulated annealing [5]; harmony search [6]; shuffled frog leaping algorithm [7]; ant colony optimization [8]; particle swarm optimization [9]; cross entropy [10]; scatter search [11]; differential evolution [12,13] and Self-Adaptive Differential Evolution [14]. In an effort to achieve better optimal solutions and reduce the computational effort with high degree of reliability in optimizing complex water distribution networks, a new evolutionary algorithm entitled "Soccer League Competition (SLC) algorithm", is introduced in the present study. Fundamental ideas of the method are inspired from soccer leagues and based on the competitions among teams and players. Like other meta-heuristic methods, the proposed technique starts with an initial population. Population individuals called player are in two types: fixed players and substitutes that all together form some teams. The competition among teams to take the possession of the top ranked positions in the league table and the internal competitions between players in each team for personal improvements are used for simulation purpose and convergence of the population individuals to the global optimum.

In this work, we examine SLC for three benchmark Water Distribution Networks (WDNs) available in the literature, and finally compare it with other meta-heuristic algorithms documented in the literature.

The optimization problems addressed herein are solved through linking the SLC algorithm with the Global Gradient Algorithm (GGA) for minimizing the design cost of water distribution systems, with pipe diameters as discrete decision variables.

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Nomenclature

$\mathbf{A}_{nn}$	coefficient matrix in GGA
$\mathbf{A}_{pp}$	diagonal matrix in GGA
$\mathbf{A}_{np}$, $\mathbf{A}_{pn}$, $\mathbf{A}_{p0}$	topological incidence sub-matrices in GGA
C	objective function
CM	Hazen–Williams coefficient
CP	Penalty function
c_i	cost of ith pipe
$\mathbf{d}_n$	column vector of demands
D_i	diameter of ith pipe
$\mathbf{D}$	diagonal matrix
$\mathbf{D}_{nn}$	diagonal matrix of derivatives of the pressure-demand with respect to $\mathbf{H}_n$
$\mathbf{D}_{pp}$	diagonal matrix of derivative of head losses with respect to $\mathbf{Q}_p$
$\mathbf{F}_n$	temporary matrix used in GGA
FP	solution vector of fixed player
G	average value of fixed player's solution vectors
h_f	head-loss
H_{min}	minimum required pressure head
$\mathbf{H}_0$	column vector of known nodal heads
$\mathbf{H}_n$	column vector of unknown nodal heads
$iter$	counter for iterations
K	number of candidate diameters
$\mathbf{L}$	lower triangular matrix
L_i	length of ith pipe
$\mathbf{M}$	pre-conditioner of the iterative method
n_l	number of loops
n_n	number of nodes with unknown heads
n_p	number of pipes
n_0	number of nodes with known heads
nT	number of teams
$nPlayer$	number of players
nFP	number of fixed players
$pp(i,j)$	power of player j in team i
PV	probability of victory
q	external demand
$\mathbf{Q}_p$	column vector of unknown pipe flow rates
Q_{in}	flow into the node
Q_{out}	flow out of the node
RP	solution vector of random player
S	solution vector of substitute
SP	solution vector of star player
SSP	solution vector of super star player
$TP(i)$	power of team i
ΔH	difference between nodal heads
λ	penalty multiplier
χ, τ	random numbers with uniform distribution

GGA is used for solving the mass and energy conservation equations [15]. The remainder of this paper is arranged as follows: Section 2 briefly presents the characteristics of the discrete pipe network optimization problems. In Section 3, the basic concepts of SLC are defined. In Section 4, we compare SLC algorithm with other meta-heuristic algorithms in terms of number of function evaluations and number of success for finding global solution in large number of runs. Finally, the conclusions are given in Section 5.

2. Problem formulation

A Water Distribution Network (WDN) is a collection of many components such as pipes, reservoirs, pumps and valves which are combined together to provide water to consumers. The optimal design of such network can be defined as determining the best combination of component sizes and settings (e.g., pipe size diameters, pump characteristic curve, pump locations and maximum power, reservoir storage volumes, etc.) that gives the minimum cost for the given layout of network, such that hydraulic laws for conservation of mass and energy are maintained and constraints on quantities and pressures at the consumer nodes are fulfilled. In this paper, water distribution network design is formulated as a least-cost optimization problem with a selection of pipe diameters as the decision variables, while pipe layout and its connectivity, nodal demand, and minimum pressure requirements are imposed. The optimization problem can be stated mathematically as [4,7,16,17]:

$$Min\ C = \sum_{i=1}^{n_p} c_i(D_i) \times L_i \tag{1}$$

where $c_i(D_i) \times L_i$ is the cost of pipe i with length L_i and diameter D_i, and n_p is the number of pipes in the network. This objective function (1) is minimized under the following constraints:

(i) Continuity equation constraint
For each junction node, a continuity equation should be satisfied,

$$\sum Q_{in} - \sum Q_{out} = q_n, \quad \forall n \in n_n \tag{2}$$

where Q_{in} and Q_{out} are flow into and out of the node, respectively, and q_n is the external demand (consumption) at the node n, and n_n is the number of nodes.

(ii) Energy conservation constraint
The total head loss or the accumulated energy loss around the closed loop (a closed loop is made by some pipes connecting together e.g., Fig. 2) should be equal to zero or the head loss along a loop between the two fixed head reservoirs (known heads) should be equal to the difference in water level of reservoirs

$$\sum_{i \in loop\ L} hf_i = \Delta H, \ \forall L \in n_l \tag{3}$$

where hf_i is the head loss due to friction in the pipe i computed by the Hazen–Williams or Darcy–Weisbach formula; n_l=loop set; ΔH=difference between nodal heads at both ends, and $\Delta H=0$, if the path is closed [12]. The Hazen–Williams formula which was used as the pressure head loss equation for pipe i of connecting nodes j and k is

$$hf_i = H_k - H_j = 10.667\ (L_i/(CM_i^{1.852} D_i^{4.871}))\ Q_i|Q_i|^{0.852} \tag{4}$$

where CM_i, D_i and L_i are pipe's Hazen–Williams coefficient (depending on the pipe material), diameter and length, respectively.

(iii) Minimum pressure constraint
For each junction node in the network, the pressure head should be greater than the prescribed minimum pressure head.

$$H_k \ge H_k^{\min}, \ \forall\ k \in n_n \tag{5}$$

where H_k is the pressure head at node k, n_n is the number of nodes, and H_k^{min} is the minimum required pressure head.

(iv) Pipe size availability constraint
The diameter of the pipes should be available from a