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# Optimum Design of Water Conveyance System by Ant Colony Optimization Algorithms

HABIBEH ABBASI, ABBAS AFSHAR, SAEED ALIMOHAMMADI
Department of Civil Engineering
Iran University of Science and Technology
Tehran, IRAN

*Abstract:* - Water conveyance systems (WCSs) are costly infrastructure in terms of materials, construction, maintenance and energy requirements. Much attention has been given to the application of optimization methods to minimize the costs associated with such infrastructure. Historically, traditional optimization techniques have been used, such as linear and non-linear programming, but within the past decade the focus has shifted to the use of evolutionary algorithms, such as genetic algorithms, simulated annealing and more recently ant colony optimization (ACO). In this paper, application of ACO algorithm on the design of water supply pipeline systems is presented. Ant colony optimization algorithms, which are based on foraging behavior of ants, is successfully applied to optimize this problem. A computer model is developed that can receive pumping stations at any possible or predefined locations and optimize their specifications. As any direct search method, the model is quite sensitive to setup parameters, hence fine tuning of the parameters is recommended.

*Key-Words:* - Water supply, Ant colony optimization, Design, Optimum, Conveyance System

## 1 Introduction

Due to the high costs associated with construction of water conveyance systems (WCSs) much research has been dedicated to the development of techniques to minimize the capital and operational costs associated with such infrastructures.

Historically, traditional optimization techniques have been used, such as linear and non-linear programming, but within the past decade the focus has shifted to the use of evolutionary algorithms, such as genetic algorithms, simulated annealing and more recently ant colony optimization (ACO).

The ant colony optimization (ACO) using principles of communicative behavior occurring in real ant colonies has been applied successfully to solve various combinatorial optimization problems namely traveling salesperson problem (e.g. Dorigo, et al., 1996) [1], the guadratic assignment problem (e.g.Maniezzo and Colorni, 1999 [2]; Gambardella, Taillard, and Dorigo, 1999a [3]), the Jab shop scheduling problem (Coloni et al., 1994) [4], or the resource-constraint project scheduling problem (Merkle, et al., 2000 [5]) (for an overview of ant algorithms see Dorigo and Di Caro,1999 [6]).

So far, very few applications of ACO algorithms to water resources problems have been reported. Abbaspour et al. (2001) [7] employed ACO algorithms to estimate hydraulic parameters of unsaturated soil. Mair et al. (2003) [8] used ACO algorithms to find a nearglobal optimal solution to a water distribution system, indicating that ACO algorithms may form an attractive alternative to genetic algorithms for the optimum design of water distribution systems. Jalali et al. (2005) [9] employed ACO to optimally operate a multi-reservoir system.

In this paper, application of ACO on the design of water supply pipeline systems is presented.

To do so, hydraulic gradient line is structured to fit an ACO model and the features related to ACO algorithms (such as heuristic information, pheromone trails, problem specific formulation, and pheromone update) will be introduced. Pressure water conveyance system and its hydraulic devices are defined with a graph and optimum solution to the system is presented.

## 2 Natural ant colonies

Ant algorithms were inspired by the observation of real ant colonies. Ants are social insects that live in colonies. An important and interesting behavior of ant colonies is their foraging behavior, and, in particular, how ants can find shortest paths between food sources and their nest [1].

While walking from food sources to the nest and vice versa, ants deposit on the ground a substance called pheromone, forming a pheromone trail [10].

Ants can smell pheromone and, when choosing their way, they tend to choose paths marked by strong pheromone concentrations. The pheromone trail allows the ants to find their way back to the food source (or to the nest). Also, other ants to find the location of the food sources found by their nestmates can use it. Considering Fig. 1A, ants are moving on a straight line that connects a food source to their nest. It is well known that the primary means for ants to form and maintain the line is pheromone trail. Ants deposit a certain amount of pheromone while walking, and each ant probabilistically prefers to follow a direction rich in pheromone. This elementary behavior of real ants can be used to explain how they can find the shortest path that reconnects a broken line after the sudden appearance of an unexpected obstacle has interrupted the initial path (Fig. 1B). In fact once the obstacle has appeared, those ants that are just in front of the obstacle cannot continue to follow the pheromone trail and therefore they have to choose between turning right or left. In this situation we can expect half the ants to choose to turn right and the other half to turn left. A very similar situation can be found on the other side of the obstacle (Fig 1C). It is interesting to note that those ants which choose, by chance, the shorter path around the obstacle will more rapidly reconstitute the interrupted pheromone trail compared to those which choose the longer path. Thus the shorter path will receive a greater amount of pheromone per time unit and in turn a larger number of ants will choose the shorter path. Due to this positive feedback process, all the ants will rapidly choose the shorter path (Fig. 1D)[1].

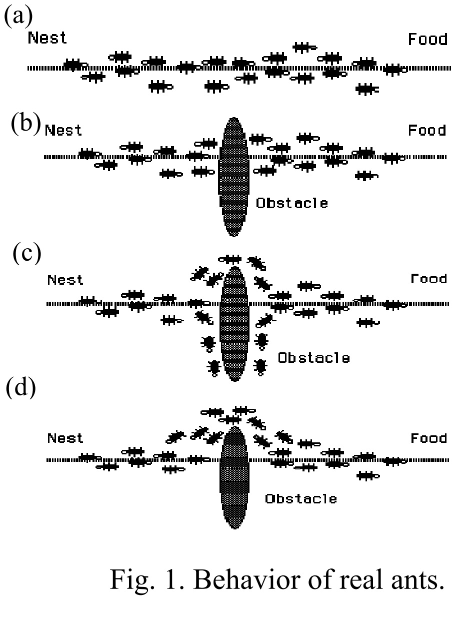

Fig. 1. Behavior of real ants.

## 3. Ant colony optimization

ACO is a metaheuristic algorithm to solve combinatorial optimization problems by using principles of communicative behavior occurring in ant colonies. Ants can communicate information about the paths they found to food sources by marking these paths with pheromone. The pheromone trails can lead other ants to the food sources.

ACO was introduced by Dorigo et al.1996. It is an evolutionary approach where several generations of artificial ants search for good solution. Every ant of a generation builds up a solution, which is found. Ants that found a good solution mark their paths through the decision space by putting some amount of pheromone on the edges of the path. Ants of the next generation are attracted by the pheromone that they will search in the solution space near good solutions.

To apply ACO to a combinatorial optimization problem, it is important to outline some basic concepts. Within ACO, the optimization problem is presented as a graph of *n* decision points where each decision point is connected to its adjacent decision point via a set of edges.

### 3.1 Ant System

Ant system (AS) [1], developed by Dorigo, Maniezzo and Colorni in 1991, was the first generation ACO algorithm. The decision policy used within AS is as follows: the probability that edge $(i, j)$ will be selected at decision point $i$ is given by:

$$P_{ij}^{k} = \begin{cases} \dfrac{(\tau_{ij})^{\alpha}(\eta_{ij})^{\beta}}{\sum\limits_{u \in N_k(r)} (\tau_{iu})^{\alpha} . (\eta_{iu})^{\beta}} & if \;\; s \in N_k(i) \\ 0 & otherwise \end{cases} \qquad (1)$$

where $p_{rs}^{k}$ is the probability that edge $(i, j)$ is chosen, $\tau_{ij}$ is the concentration of pheromone associated with edge $(i, j)$, $\eta_{ij}$ is the desirability of edge $(i, j)$, $N_k(i)$ is the feasible neighborhood of ant $k$ when located at decision point $i$, and $\alpha, \beta$ are the parameters controlling relative importance of the pheromone intensity and desirability for each ants decision. If $\alpha >> \beta$ then the algorithm will make decisions based mainly on the learned information, as represented by the pheromone and if $\beta >> \alpha$ the algorithm will act as a greedy heuristic

selecting mainly the shortest or cheapest edges, disregarding the impact of these decisions on the final solution quality [11].
when each ant has generated a solution ( i.e. at the end of an iteration) the pheromone on each edge is updated. The pheromone updating equation for AS is given by

$$\tau_{ij} = \rho\tau_{ij} + \Delta\tau_{ij} \qquad (2)$$

where $\rho$ is the coefficient representing pheromone persistence (note: $0 \le \rho \le 1$) and $\Delta\tau_{ij}$ is the pheromone added for edge $(i, j)$. The pheromone persistence factor is the mechanism by which the pheromone trails are decayed, enabling the colony to 'forget' poor edges and increasing the probability of selecting good edges [12]. For $\rho \to 1$ only small amounts of pheromone are decayed (evaporated) between iterations and convergence rate is slower, whereas for $\rho \to 0$ more pheromone is decayed (evaporated) resulting in faster convergence. $\Delta\tau_{ij}$ is a function of the solutions found and is given by :

$$\Delta\tau_{ij} = \sum_{k=1}^{m} \Delta\tau_{ij}^{k} \qquad (3)$$

Where $m$ is the number of ants and $\Delta\tau_{iij}^{k}$ is the pheromone addition laid on edge $(i, j)$ by the $k^{th}$ ant:

$$\Delta\tau_{ij}^{k} = \begin{cases} \dfrac{Q}{f(S_k)} & if\,(i, j) \in S_k \\ 0 & otherwise \end{cases} \qquad (4)$$

where $Q$ is the pheromone additions factor (a constant) and $S_k$ is the set of edges selected by ant $k$ and $f(\cdot)$ is the objective function.

### 3.2 Ant Colony System

Ant Colony System (ACS) is one of the first successors of AS. It introduces three major modifications into AS [11]:
1.ACS uses a different decision policy [12]. Let $k$ be an ant located at a decision point $i$, $q_0 \in [0,1]$ be a parameter, and $q$ a random value in $[0,1]$. The next decision point $j$ is randomly chosen according to the following probability distribution

$if\;\; q \le q_0$ :

$$P_{ij}^{k} = \begin{cases} 1 & if\; s = \boldsymbol{arg}\; \underset{u \in N_k(i)}{\boldsymbol{max}} (\tau_{iu})^{\alpha} \cdot (\eta_{iu})^{\beta} \\ 0 & otherwise \end{cases} \qquad (5)$$

$else(q > q_0)$:

$$P_{ij}^{k} = \begin{cases} \dfrac{(\tau_{ij})^{\alpha} (\eta_{ij})^{\beta}}{\sum_{u \in N_k(i)} (\tau_{iu})^{\alpha} . (\eta_{iu})^{\beta}} & if\;\; j \in N_k(i) \\ 0 & otherwise \end{cases} \qquad (6)$$

As can be seen, the rule has a double aim: when $q \le q_0$, it exploits the available knowledge, choosing the best option with respect to the heuristic information and the pheromone trail. However, if $q > q_0$, it applies a controlled exploration as done in AS.
2. The pheromone update is done by first evaporating the pheromone trails on all connections used by the global-best ant (it is important to notice that in ACS, pheromone evaporation is only applied to the connections of the solution that is also used to deposit pheromone) as follows:

$$\tau_{ij} = (1 - \rho)\tau_{ij} + \rho . f(S_{global-best})\;\; \forall a_{ij} \in S_{global-best} \qquad (7)$$

3.Ants apply local updating that encourages the generation of different solutions to those yet found. Each time an ant travels an edge $(i, j)$, it applies the following rule [13]:

$$\tau_{ij} = (1 - \varphi)\tau_{ij} + \varphi\,\tau_0 \qquad (8)$$

Where $\varphi \in (0,1]$ is a second pheromone decay parameter. The application of local updating makes the pheromone trail on the connections traversed by an ant decrease. Hence, this results in an additional explorations technique of ACS by making the connections traversed by an ant less attractive to following ants and helps to avoid that every ant follows the same path.

## 4. Application of Ant Colony Optimization to Water Conveyance System Optimization

The optimization of WCSs is defined as the selection of the lowest cost combination of appropriate sizes of the pipeline and hydraulic devices (i-e, pumps) and component setting such that design constraints are satisfied.
The decision variables have primarily been selected as the friction head loss and dynamic pumping head within any branch. The design constraints on the system have normally been the requirement of minimum allowable pressures and the maximum

allowable pressures at each node. In addition to the design constraint the hydraulic equations governing fluid flow must also be satisfied.

### 4.1 Modification of ACO elements

ACS is applied for optimization of WCSs. The fitness function is a measure of goodness of the generated solutions according to defined objective function. For this study, total cost $(C_k)$ of pipes and pumping stations in every decision point is defined as:

$$C_k = \sum_{N=1}^{NS} C(N) = \sum_{N=1}^{NS} \left[FCP^k(HP(N))\right] + \left[CPD^k(N) \times L(N)\right] \tag{9}$$

Where $FCP^k(HP(N))$ is the cost of pumping station for node $N$ that is proportional to pumping head, $CPD^k(N)$ is the unit cost of pipe and $L(N)$ is the length of pipe. $NS$ is the total number of topography nodes.

The objective function is to minimize cost; cheaper options are more desirable. The heuristic information on this problem is determined by:

$$\eta_{ij} = 1 - \frac{C_{ij}}{\sum_{l \in N_k(i)} C_{il}} \tag{10}$$

Where $C_{ij}$ is the cost of transfer from $i$ to $j$, $N_k(i)$ is the feasible neighborhood of ant $k$ when located at decision point $i$.

At first the amount of pheromone on all paths are equal (i.e., $\tau_\circ = 1$). In other words all paths have same preference for ants. After solutions are generated the pheromone added for edge $(i,j)$ $(\Delta\tau_{ij})$ belongs to global best solution depends on its quality:

$$\Delta\tau_{ij} = \frac{Q}{C_{global-best}} \tag{11}$$

where $Q$ is pheromone reward factor, $C_{global-best}$ is the total cost of global best solution.

## 6. Case study

The WCSs is a gravity system and consists of 12 nodes. The gradient hydraulic line is divided into 50 classes with 1 meter interval. The allowable extent of velocity is 0.4 to 2.6 meter per second and the minimum allowable pressure at each node is 3 meters. The results of applying ACS in this case study has been shown in tables 1 and 2. Figure 1 shows the grade line and elevation of the conveyance system.

As is clear from column 4 of table (1) the maximum allowable velocity (2.4 m/s) restricts the pipe diameters in 0.4004 m. So there is no possibility to further decrease the total cost and it is the global optimum solution.

### 6.1 Parameter settings

The Sensitivity parameters analysis was set as follows for ACS within this study case; $\tau_o = 1$، $\rho = 0.1$، $\varphi = 0.9$ ، $q_\circ = 0.8$ ،$\alpha = 1$،$\beta = 3$

## 7 Conclusions

Ants can communicate information about the paths they found to food sources by marking these paths with pheromone. The pheromone trails can lead other ants to the food sources.

Within this paper, application of ACS for WCSs is presented. It is shown to be effective.

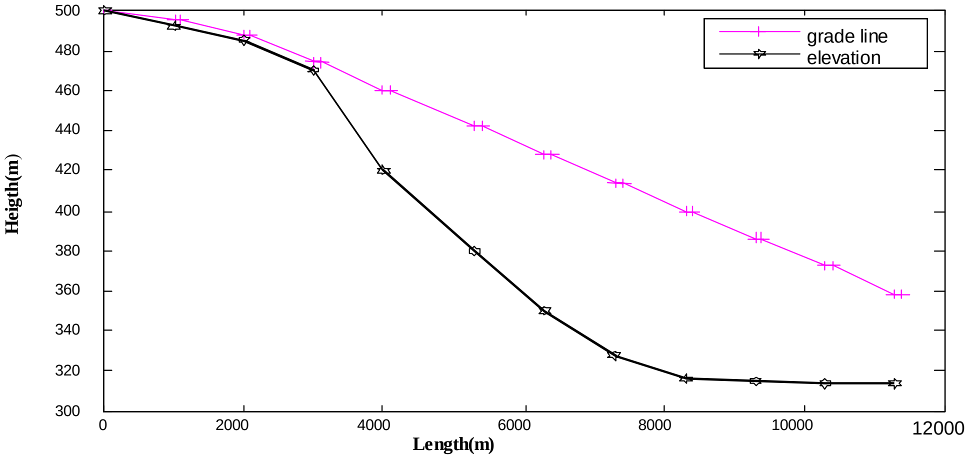

Figure 1: The optimal design of the gravity case study

Table 1: Results of application ACS to the gravity case study

| NO. BRANCHE | Diameter(m) | Length(m) | V(m^3/S) |
|---|---|---|---|
| 1 | 0.4947 | 1000 | 1.562 |
| 2 | 0.4617 | 1000 | 1.793 |
| 3 | 0.4004 | 1000 | 2.384 |
| 4 | 0.4004 | 1000 | 2.384 |
| 5 | 0.4013 | 1300 | 2.373 |
| 6 | 0.4004 | 1000 | 2.384 |
| 7 | 0.4004 | 1000 | 2.384 |
| 8 | 0.4004 | 1000 | 2.384 |
| 9 | 0.4004 | 1000 | 2.384 |
| 10 | 0.4004 | 1000 | 2.384 |
| 11 | 0.4004 | 1000 | 2.384 |

Table 2: Continue results of ACS application to the gravity case study

| NO. NODE | Hpump(m) | Elevation(m) | NET HEAD (m) |
|---|---|---|---|
| 1 | 0 | 500 | 0 |
| 2 | 0 | 492 | 3 |
| 3 | 0 | 485 | 3 |
| 4 | 0 | 470 | 4 |
| 5 | 0 | 420 | 40 |
| 6 | 0 | 380 | 62 |
| 7 | 0 | 350 | 78 |
| 8 | 0 | 328 | 86 |
| 9 | 0 | 316 | 84 |
| 10 | 0 | 315 | 71 |
| 11 | 0 | 314 | 58 |
| 12 | 0 | 314 | 44 |
|  |  |  | **TOTALCOST=117836** |

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