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APPLICATION OF NA-ACO IN MULTIOBJECTIVE CONTAMINANT SENSOR NETWORK DESIGN FOR WATER DISTRIBUTION SYSTEMS

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Abstract

Using contaminated drinking water as a weapon against consumers has a long line in history. Among different issues threatening water distribution networks, the most complex ones are deliberate injection of chemical or biological contaminants into distribution water networks as there is uncertainty about contaminant type, starting location of contamination in network, starting and ending time of contamination event, and results of attacks. In this study for the first time we introduced a technique for design of contaminant sensor networks in water distribution systems using a multi objective multi ant colony optimization approach. This article presents the Non-dominated Archiving Ant Colony Optimization (NA-ACO) for solving the multi objective sensor placement problem. An example network is used to demonstrate the functionality of the proposed method and the Pareto solutions derived using the NA-ACO algorithm is presented.

Keywords

Sensor, Contaminant, Water Distribution Systems, NA-ACO, Multiobjective Optimization

1. INTRODUCTION

Using contaminated drinking water as a weapon against consumers has a long line in history. During the First Sacred War in Greece, in about 590 BC, Athens and the Amphictionic League poisoned the water supply of the besieged town of Kirrha (near Delphi) with the toxic plant hellebore (Mayor, 2003). The Roman commander Manius Aquillus poisoned the wells of besieged enemy cities in about 130 BC (Arnold, 2002). Three veterans of Unit 731 (a covert biological and chemical warfare research and development unit of the Imperial Japanese Army that undertook lethal human experimentation during the Second Sino-Japanese War (1937–1945) and World War II) testified, in a 1989 interview to the Asahi Shimbun, that they were part of a mission to contaminate the Horustein river with typhoid near the Soviet troops during the Battle of Khalkhin Gol (Gold, 1995). During 1998-1999 Kosovo conflict, over 10,000 wells have been contaminated with animal and human remains or other toxic materials (ICRC, 1999). In March 2006 Residents of Blackstone and North Smithfield were ordered to stop using water from their taps after someone broke into the area's supply facility and left behind a 5-gallon container that had an odor. Three teenagers were arrested in Blackstone Water Vandalism Case (The Boston Channel, 2006). On Nov. 24 2009, radioactive tritium was intentionally placed in a water cooler at India's Kaiga nuclear power plant. Tritium was discovered inside the water dispenser, which was located near a closely monitored reactor at the site. Up to 55 workers are believed to have consumed the tainted water. The contamination of drinking water at Kaiga nuclear power plant in Uttara Kannada district was an act of sabotage carried out by some disgruntled employee (The pioneer, 2009).

Acts of contamination may occur at the reservoirs, intake structures, treatment plants, or within the distribution systems. Contamination of a large water reservoir would unlikely produce a large risk to public health because of the dilution effect, filtration, and disinfection of the water. A successful attack would likely involve either disruption of the water treatment process like destruction of plumbing, or release of disinfectants or post-treatment contamination near the target. Pipes downstream from the treatment plant are vulnerable (Dick, 2001).

In recent years researches resulted in significant improvements in water quality sensors. These sensors work better and faster in contrast with older models and they are more reliable. The main problem in using these new sensors is the high purchasing, installation, and maintenance expenses. In addition to financial limitations there are other design requirements that must be taken into account. Maximum water security must be provided to the public. Contamination events must be detected as fast as possible and all possible threats need to be covered. We therefore need algorithmic methods to find the optimum layout of sensors network in water distribution systems.

For this purpose different models are presented and each tries to cover the mentioned problems. Lee and Deininger (1992) developed a method based on Demand Coverage concepts. Kumar et al (1997) also used Coverage Matrix which was developed by Lee and Deininger by offering some changes in the methodology.

Kessler et al (1998) introduced a new term in their studies, Level of Service. Level of Service is the maximum volume of water which is allowed to pass through a specific node according to detection time before water contamination is detected by a sensor. After hydraulic simulation of water flow in the network, a directed graph will be constructed which will be used instead of the real network in solving the problem.

Berry et al (2003) presented a model for optimizing the placement of sensors in municipal water networks in which they considered a sensor placement formulation for which optimal sensor configurations minimize the expected fraction of the population that is at risk for an attack. They weighted each node by the number of people potentially consuming water at that point and used a mixed-integer programming model to exactly solve it. In a separate study, Berry et al (2004) introduced a new Integer Programming based model for solving the problem. Their model requires a risk profile, which is a probability distribution that weights the likelihood of an attack at a specific node at a specific time. This model minimizes the number of people exposed to a dangerous level of contamination.

Al-Zahrani and Moied (2003) developed the Lee and Deininger's model. They solved the problem under multiple flow scenarios considering that flow demands in a water distribution network vary during the day. They solved the optimization problem using Genetic Algorithms. Ostfeld and Salomons (2004) presented a methodology for finding the optimal layout of an early warning detection system. They considered extended period unsteady hydraulics and water quality conditions for solving the optimization problem. This model is capable of solving the sensor problem under multiple injections (up to three injections) per pollution event. A given defensive level of service to the public was defined as a maximum volume of contaminated water exposure at a concentration above a minimum level. They used Genetic Algorithms for solving the optimization problem.

Propato (2006) introduced Mixed-Integer Linear Models for Sensor Location Design. Afshar et al (2006) developed a model using Ant Colony Optimization (ACO) algorithm for the first time. Their model was based on Al-Zahrani and Moied (2003) and Lee and Deininger (1992) researches results. In The Battle of the Water Sensor Networks (BWSN) (Ostfeld et al, 2008) a comparison was made between different models efficiency and reliability. Aral Et al (2010) used an optimization algorithm based on a simulation-optimization and a single-objective function approach which incorporates multiple factors used in the design of the system. They also introduced a reliability constraint concept into the optimization model such that the minimum number of sensors and their optimal placement can be identified in order to satisfy a pre specified reliability criterion for the network.

Ant Colony Optimization techniques is a novel meta-heuristic method introduced recently for solving complex optimization problems (Dorigo, 1992; Dorigo et al, 1996). Gambardella et al (1999) presented

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MACS-VRPTW; an Ant Colony Optimization based approach useful to solve vehicle routing problems with time windows. The method was organized with a hierarchy of artificial ant colonies designed to successively optimize a multiple objective function. The first colony minimized the number of vehicles and the second colony minimized the traveled distances. Mariano and Morales (2000) introduced a new algorithm called MDQL, for the solution of multiple objective optimization problems. The algorithm was based on a distributed Q learning algorithm, called DQL. They used a non-dominant criterion to construct Pareto front.

Iredi et al (2001) proposed a new approach to solve bi-criterion optimization problems with ant algorithms. They used several colonies of ants for finding good solutions and introduced two methods for cooperation between the colonies. T'kindt et al (2002) proposed an Ant Colony Optimization approach to solve the 2-machine flow shop scheduling problem. Guntsch1 and Middendorf (2003) proposed a Population-based Ant Colony Optimization (PACO) approach to solve multi-criteria optimization problems and to find a set of different solutions which covers the Pareto-optimal front. The population of solutions was chosen from the set of all non-dominated solutions found so far. Lopez-Ibanez et al (2004) studied the performance of several ACO variants for the bi-objective Quadratic Assignment Problem that was based on two different search strategies.

Jalali et al (2007) combined a multi-colony scheme into the original ACO algorithms to address the optimum operation of a multi-reservoir system with continuous search space. Afshar et al (2009) presented Nondominated Archiving Multicolony Ant Algorithm for multiobjective optimization problems and tested the algorithm with large scale time–cost trade-off problems in construction optimization. Pareto archiving together with innovative solution exchange strategy were introduced. Also Afshar et al (2009) tested NA-ACO performance employing the optimization of reservoir operating policy problem with multiple objectives (i.e. flood control, hydropower generation and irrigation water supply).

In this study we took into consideration two main objectives: (1) Maximizing Detection Likelihood and (2) Minimizing Expected Time to Detection. We introduce a new technique based on Non-dominated archiving multi-colony ant algorithm for multi-objective Optimization for solving the sensor problem. We assume that when a contamination event is detected, a general warning system will raise an alarm and water consumption will stop immediately. Also we assume that sensors are ideal and do not fail to detect a contamination event when polluted water is passing by. With regards to the mentioned objectives in solving the sensor problem, the probability of detection of a contamination event will be maximized and general warning will ban water consumption as fast as possible so number of casualties and amount of damages following a probable attack will be minimized.

2. PROPOSED OPTIMIZATION TECHNIQUE

In this study we use the following definitions for the proposed design objectives (Ostfeld et al, 2008):

2.1 Detection Likelihood; Z_1:

In summary, we can define Detection Likelihood in a sensor network as the probability of detection of a contamination event in water distribution system by at least one sensor. In other words, with regards to this objective, best solution may be obtained when proposed sensor layout can detect every attack on network.

Assuming a specific water distribution system and a defined layout for sensor network, the detection likelihood is estimated by:

$$Z_1 = \frac{1}{A}\sum_{r}^{A} d_r \qquad (1)$$

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Where d_r equals 1 if contamination event r is detected by sensors network, and zero if contamination event r is not detected. A is the total number of contamination events considered. Z_1 should be maximized.

2.2 Expected Time to Detection; Z_2:

For a particular contamination scenario, the detection time (t_i) for a specific sensor placed in location i, is the time interval between the start of the contamination event and the first detection of contaminant presence in water distribution system by that sensor. The detection time for a sensor network (T_d) is estimated by:

$$\mathbf{T_d} = \begin{cases} 0 & \text{contamination event is not detected} \\ \min t_i & \text{contamination event is detected} \end{cases} \qquad (2)$$

As previously mentioned, contamination detection means to ensure that at least one of the sensors will be activated while contaminated water is passing through the water network. Thus for detection of a contamination event, firstly at least one sensor is needed to be present in contaminated water path through network and secondly the concentration of contaminant must be above the minimum concentration that sensors are able to detect. The objective function to be minimized which is the Expected Time to Detection is estimated by:

$$Z_2 = \frac{1}{A_d} \sum_{i}^{A_d} T_d \qquad (3)$$

A_d is the number of contamination events which are detected by the sensor network. In this formulation we ignore the effects of undetected contamination events.

Moreover a constraint is considered in this problem which is total number of sensors equals S and S is a constant value. In this way placing more than one sensor in a single node is impossible. Application of these methods is illustrated by solving the problem for an example water distribution network.

3. APPLICATION OF NA-ACO

For solving a problem using ACO metaheuristics we need to represent the optimization problem as a graph. In this study we use a method introduced by Afshar et al (2006) for this purpose. The proposed graph is an $N \times S$ graph where S is the total number of sensors and N is the total number of nodes in the network. As it mentioned before it is not allowed to place more than one sensor in one node. In Figure 1 an example graph is illustrated for a water distribution network consisted of 15 nodes (N=15) and 10 sensors (S=10). In addition two possible paths for ants to cross are presented.

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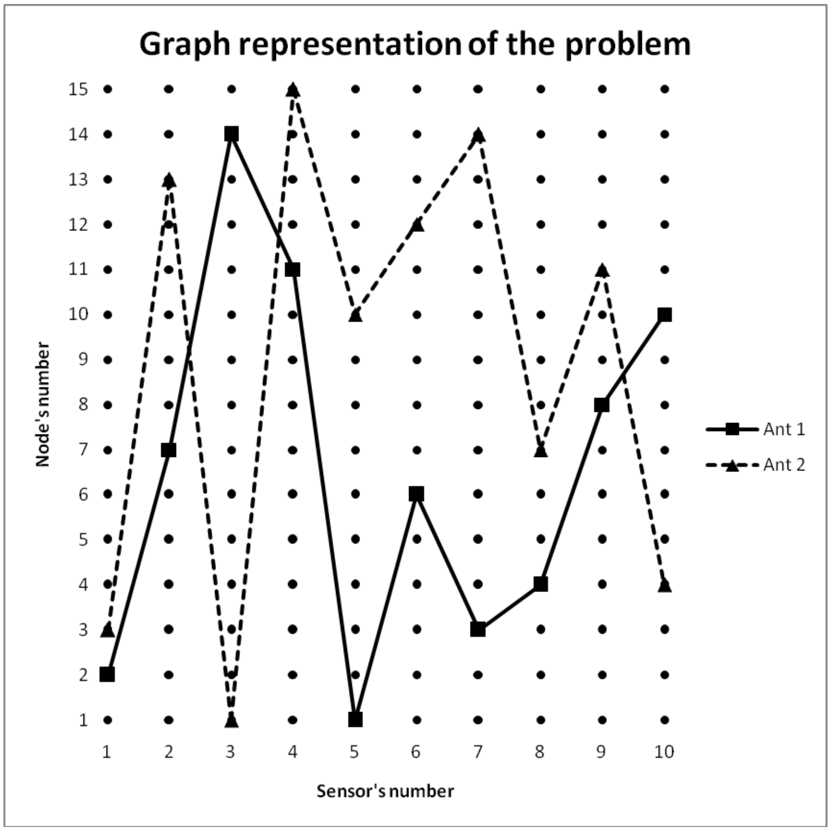

Figure 1. Graph representation of the problem

We used $N \times S$ matrices proportional to the graph as pheromone matrices. The procedure of solving the problem using NA-ACO is illustrated in Figure 2 and is as follows:

Step 1: As NAACO uses two separate colonies for optimization, in the beginning an initial pheromone value is designated to each colony. In solving the example problem $\tau_{ij,1}=\tau_{ij,2}=1$. In this step a set of random solutions is produced and imported to the first colony.

Step 2: In colony 1 best ant will be chosen according to best value of Z_1 . This ant solution will transfer to Archive 1.

Step 3: The pheromone value for first colony will be updated according to best ant in that trial.

Step4: The pheromone value for first colony will be updated according to best ant in Archive 1.

Pheromone updating is performed as:

$$\tau_{ijk}(t+1) = \rho\tau_{ijk}(t) + \Delta\tau_{ijk} \qquad (4)$$

Where k refers to the colony under consideration, the parameter $\rho \in (0, 1]$ regulates the pheromone evaporation. $\tau_{ij\,k}(t)$ is the total pheromone deposited on path ij at time t in colony k and $\Delta\tau_{ij\,k}$ represents the updating value of pheromone on edge ij for colony k as:

$$\Delta\tau_{ijk} = \begin{cases} \dfrac{Q_k}{f^k(B)} & \text{if (i, j) is travelled by the best ant} \\ 0 & \text{otherwise} \end{cases} \qquad (5)$$

Where Q_k is a constant, representing the amount of pheromone that the best ant puts on the path after an

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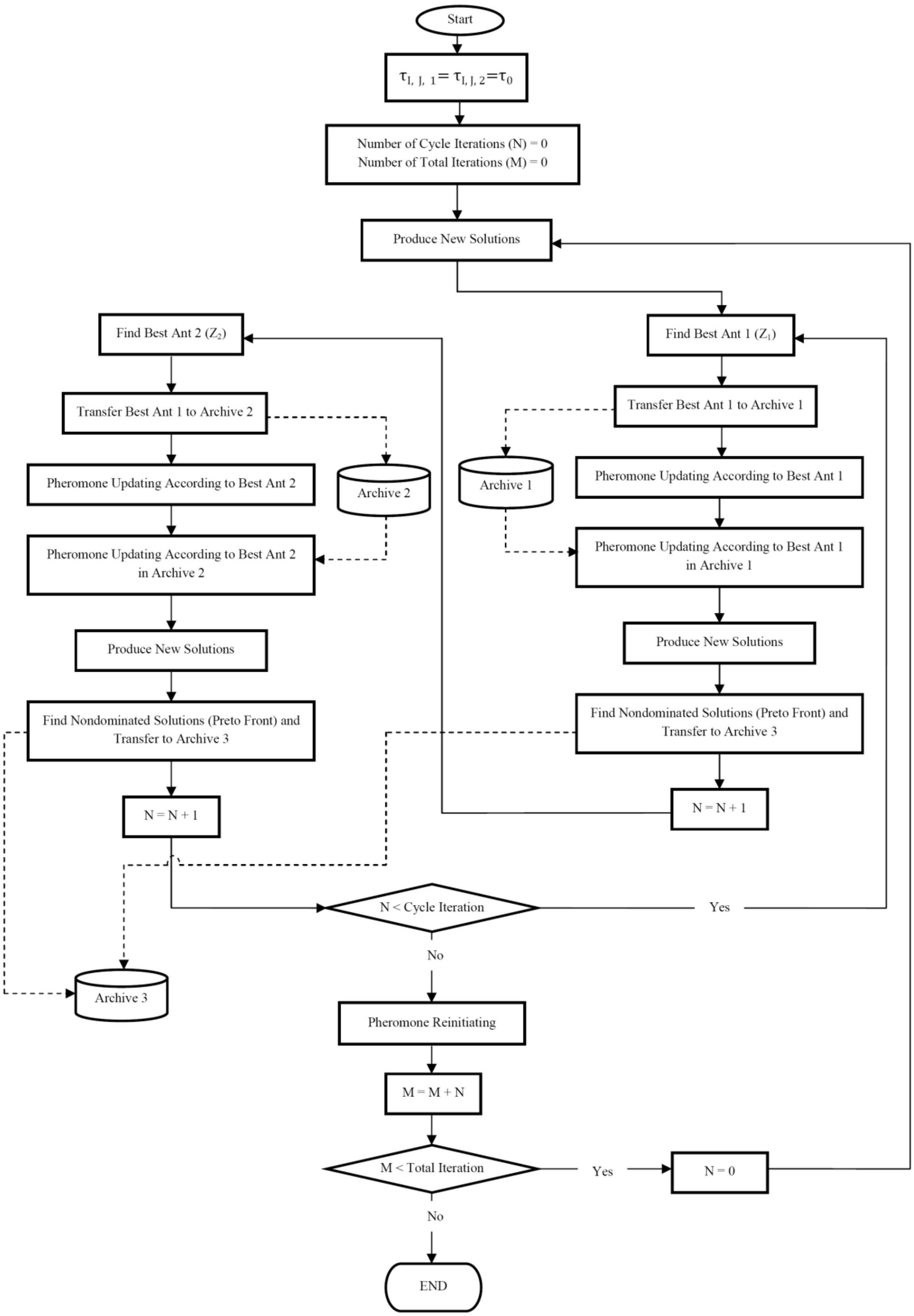

Figure 2. Flowchart of the complete process of the NA-ACO algorithm.

exploitation in the colony number *k*, and $f^{k}(B)$ is the best value of objective *k* in each iteration.

Step 5: New solutions are generated. The probability of each edge being selected by the agents of colony *k* is defined as:

$$P_{ijk}(t)=\begin{cases}\dfrac{[\tau_{ijk}(t)]^{\alpha}\,[\eta_{ijk}(t)]^{\beta}}{\sum_{l\in allowed}[\tau_{ilk}(t)]^{\alpha}\,[\eta_{ilk}(t)]^{\beta}} & \text{if } j\in \text{allowed}\\[2ex] 0 & \text{otherwise}\end{cases} \qquad (6)$$

in which $P_{ij\,k}(t)$ is the probability of edge *ij* being selected by an agent in colony *k* at iteration *t* , and $\eta_{ij\,k}(t)$ is the heuristic value of path *ij* at time *t* according to the measure of the objective function *k* (for colony *k*). α and β are parameters that control the relative importance of the pheromone trail versus a heuristic value. Let *q* be a random variable uniformly distributed over [0, 1], and q0 ∈ [0, 1] be a tunable parameter. The next node *j* that an ant of colony *k* chooses to go is:

$$j=\begin{cases}\arg_{l\in allowed}\max\{[\tau_{ilk}(t)]^{\alpha}\,[\eta_{ilk}(t)]^{\beta}\} & \text{if } q\le q_0\\[1ex] J & \text{otherwise}\end{cases} \qquad (7)$$

Where *J* is a random variable selected according to the probability distribution of $P_{ij\,k}(t)$.
Step 6: Optimum Pareto front is derived according to both objectives. The Pareto solution will be transferred to Archive 3.
Step 7: Ants of Colony 1 will be transferred to Colony 2. All steps in Colony 2 are as same as colony1. Best ant solution for Colony 2 will be transferred to Archive 2.
Step 8: Ants produced in Colony 2 will be transferred to Colony 1. The cycle continues for N iterations.
Step 9: After each N iterations the pheromone value for both colonies will be reinitiated ($\tau_{ij,1}=\tau_{ij,2}=1$). The cycle continues for M iterations.
Step 10: Optimum Pareto front is derived according to solutions in Archive 3. This will be the final solution for the optimization problem.

4. EXAMPLE NETWORK

The methodology is presented using EPANET 2.0 example 3 shown in figure 3. EPANET 2.0 example 3 consists of 97 nodes. Each node is a possible location for sensor placement and also an attack is probable to occur in every node. In this study 1164 attacks (A=1164) are modeled. Each attack consists of a single contaminant injection in only one node at the mass rate of 200 gr/min and for a 2 hours interval. For each network's node, 12 contamination events are modeled. Injection starting time is at 0, 2, 4, …, 20, 22. For this example the total number of sensors, S, is equal to 10.
The first step for solving the problem is quality analysis of water distribution system under 1164 contamination events. In this study EPANET Programmer's Toolkit Version 2.00.07 (January 2001) is used for analyzing the water quality behavior of water distribution system. All analyses are performed for the system's extended period simulation timeframe, 24 hours. As a result t_{max} in Z_3 equals 24 hours or 1440 minutes.
After analyzing the water quality behavior of network, it is time for constructing the contamination matrix using the obtained results. For this purpose we used contamination matrix introduced by Ostfeld and Salomons (2004). We assumed that sensors are perfect and able to detect any contamination if its

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concentration in sensor's location is above 1 mg/L. A contamination is an N × A matrix of 0–1 coefficients, where N is the number of nodes and A is the number of contamination events considered. The rows of the matrix list all contamination events, while the columns list all nodes. As mentioned before, in this example N = 97 and A = 1164.
In each attack during simulation time (24 hours), if contaminant concentration in a node rises above the minimum level of 1 mg/L, that node is considered contaminated. It means that the correspondent element of that node and attack in contamination matrix equals 1. Otherwise the node is considered uncontaminated and the correspondent element in contamination matrix equals 0.
Using contamination matrix for a specific attack scenario and sensor layout, if at least one sensor is presented at a contaminated node, that event will be detected. Otherwise the contamination event will remain undetected. Using this information and Z_1 formula, detection likelihood for sensor layout can be determined.

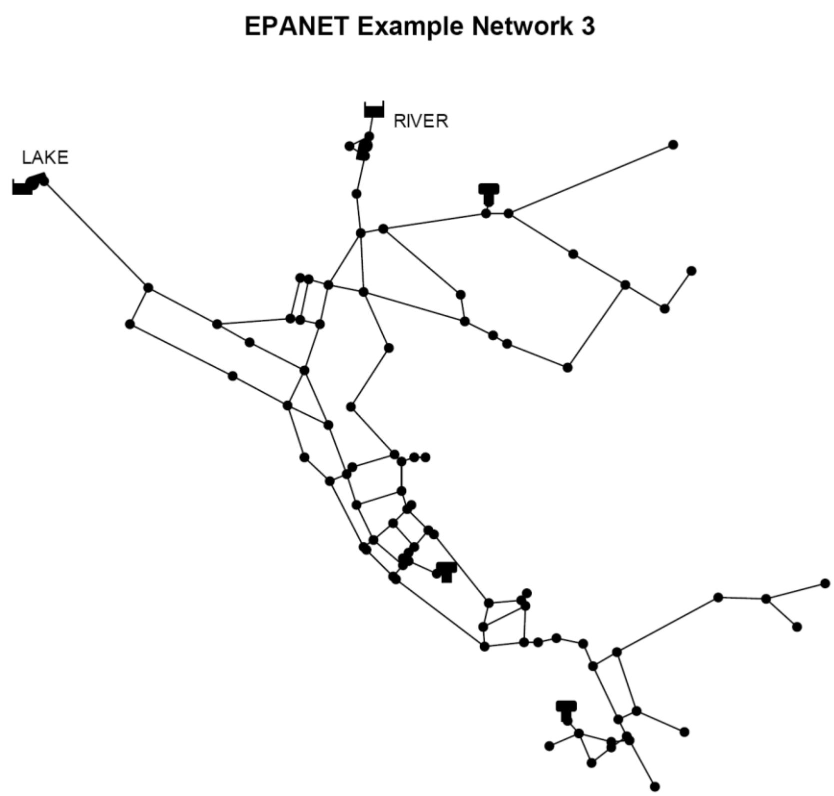

Figure 3. EPANET 2.0 example 3

If the contamination event is detected, by using EPANET's water quality analysis results and sensor network layout, the detection time (t_i) for a specific sensor placed in location i may be determined and as a result min t_i and T_d may be determined.
As it is mentioned before for solving the optimization problem using NAACO we need to represent the optimization problem as a graph. The graph used for solving the example problem is like the graph illustrated in Figure 1. The only difference is that in this example number of nodes is 97 instead of 15.
For this example each colony has 500 ants. The values for N and M in Figure 2 are respectively 20 and 100. It means that there are totally 10 internal cycles and 5 external cycles. As heuristic value is not available for this problem, β equals zero and as a result α equals one. Pareto solutions derived using the Non-dominated Ant Colony Optimization algorithm (NAACO) is illustrated in Figure 4.

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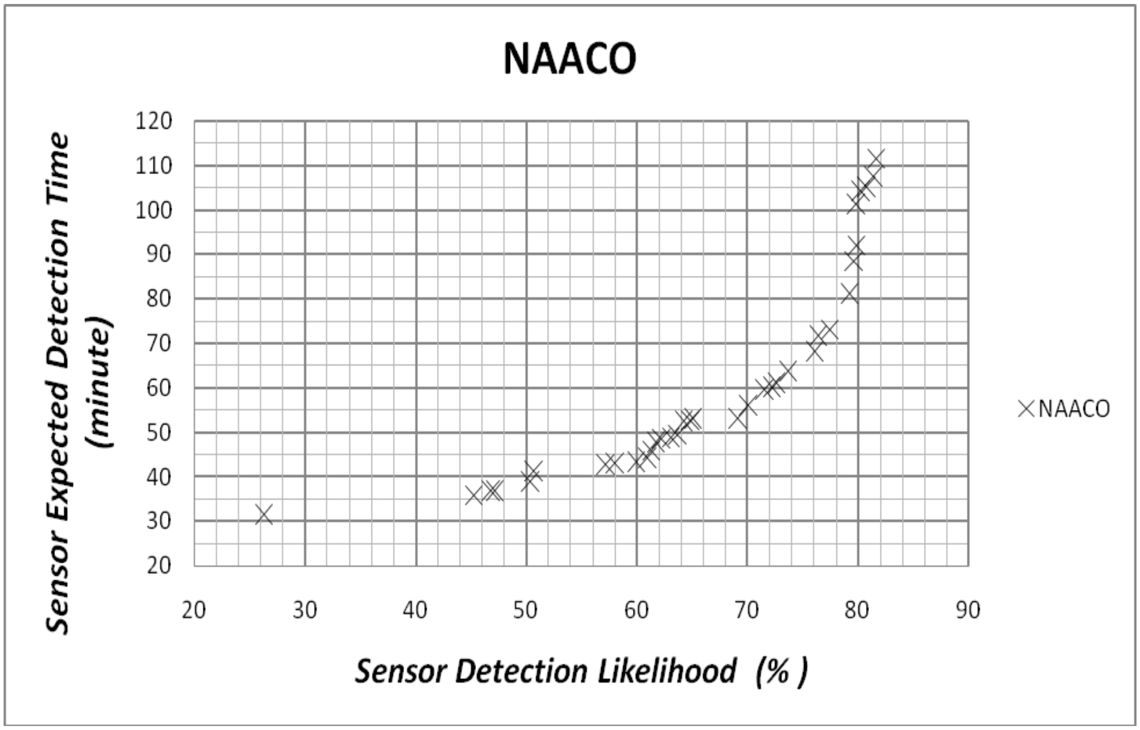

Figure 4. Pareto solutions derived using the Non-dominated Ant Colony Optimization algorithm

5. Conclusion

In this study we used a multi objective ant colony optimization for designing a contaminant sensor network in water distribution systems for the first time. For this purpose we took the advantages of Non-dominated Archiving multi-colony ant algorithm (NA-ACO) for solving the multi-objective optimization problems. Considering different objectives that may be used for solving the problem, we chose (1) Detection Likelihood and (2) Expected Time to Detection as the most important parameters in solving the problem. EPANET 2.0 example 3 network is used as an example water distribution system for solving the sensor problem using proposed method.

For finding the real optimum solutions and reducing computational expenses many suggestions may be offered that could each be a subject for future studies. Considering the presented uncertainties in the real world may cause major changes in final solution and make the designed sensor network to become more reliable. In this study and most former studies, sensors are considered ideal. Considering real features of a sensor, like delay in detection of contamination and false detection, may have a major impact on solutions reliability.

As we mentioned before we did not used heuristic parameter for solving the problem. Introducing this parameter in this problem while using ACO algorithms may lead to great decrease in computational expenses and result in a faster convergence of the algorithm. At the end using new metaheuristic techniques is an open area of research in the field.

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