Split-Pipe Design of Water Distribution Networks Using a Combination of Tabu Search and Genetic Algorithm

J. Tospornsampan, I. Kita, M. Ishii, Y. Kitamura

***Abstract*—**In this paper a combination approach of two heuristic-based algorithms: genetic algorithm and tabu search is proposed. It has been developed to obtain the least cost based on the split-pipe design of looped water distribution network. The proposed combination algorithm has been applied to solve the three well-known water distribution networks taken from the literature. The development of the combination of these two heuristic-based algorithms for optimization is aimed at enhancing their strengths and compensating their weaknesses. Tabu search is rather systematic and deterministic that uses adaptive memory in search process, while genetic algorithm is probabilistic and stochastic optimization technique in which the solution space is explored by generating candidate solutions. Split-pipe design may not be realistic in practice but in optimization purpose, optimal solutions are always achieved with split-pipe design. The solutions obtained in this study have proved that the least cost solutions obtained from the split-pipe design are always better than those obtained from the single pipe design. The results obtained from the combination approach show its ability and effectiveness to solve combinatorial optimization problems. The solutions obtained are very satisfactory and high quality in which the solutions of two networks are found to be the lowest-cost solutions yet presented in the literature. The concept of combination approach proposed in this study is expected to contribute some useful benefits in diverse problems.

***Keywords*—**GAs; Heuristics; Looped network; Least-cost design; Pipe network; Optimization; TS

I. Introduction

DURING the last two decades, several new optimization methods based on heuristic search techniques have been proposed and widely used to solve approximately complex combinatorial optimization problems encountered in a variety of real-life applications. Heuristic techniques are iterative search processes that attempt to avoid becoming trapped in local optima by employing different efficient strategies of their own techniques. Advantage of heuristic optimization techniques over the conventional optimization techniques are their robustness, fast, flexibility and capability of solving large and complex combinatorial problems while classical optimization methods often encounter great difficulty when faced with the challenge of solving hard problems that abound in the real world. Anyhow, heuristic techniques do not guaranteed the optimal solutions. Major representatives of these heuristic-based optimization methods include genetic algorithms (GAs) (Goldberg [12]; Michalewicz [18]) simulated annealing (SA) (Kirkpatrick et al. [15] and tabu search (TS) (Glover and Laguna [11]). These methods have gained much attention due to their efficiency and success in solving complex and difficult problems.

In this paper, a combination approach of TS and GA is proposed to obtain the least cost design of water distribution network based on the split-pipe design. The water distribution network problem is a combinatorial problem, that is, a set of solutions must be selected from a discrete set of feasible solutions while the functions represent the hydraulic behavior of the network are nonlinear. The solution process involves simultaneous consideration of continuity equation, energy conservation, and head-loss function that makes the analytical solution of the problem becomes complicated.

In engineering practice, a single pipe should be selected for the entire length of each link, but if this is done, the design will not be optimal. It can be shown that at the optimum, each link will contain at most two segments, their diameters being adjacent on the candidate list for that link (Alperovits and Shamir [1]). The use of a heuristic based technique to obtain the optimal split-pipe design has been previously initiated by Tospornsampan et al. [27]. In that paper, the SA was implemented by which a set of pipe segment diameters was selected directly from a specified set of commercial pipe diameters while a set of pipe segment lengths was explored simultaneously. In the present work, a set of pipe segment diameters is derived by a TS while a set of pipe segment lengths is derived by a GA. TS has been successfully applied to solve combinatorial optimization problems mostly involve integer variables problems. The technique can be applied to continuous variables problems by discretization of continuous variables into discrete variables. Anyhow, TS is inherently

J. Tospornsampan is with TEAM Consulting Engineering and Management Co., Ltd. 151 TEAM Building, Nuan Chan Rd., Khlong Kum, Bung Kum, Bangkok, 10230 Thailand (phone: 66-2-509-9000; fax:66-2-509-9045; e-mail: janejira_t@team.co.th).

I. Kita is with Faculty of Life and Environmental Science, Shimane University, Matsue, Shimane, 690-8504 Japan (e-mail: kita@life.shimane-u.ac.th).

M. Ishii is with Faculty of Life and Environmental Science, Shimane University, Matsue, Shimane, 690-8504 Japan (e-mail: ici@life.shimane-u.ac.th).

Y. Kitamura is with Faculty of Agriculture, Tottori University, Koyama-minami, Tottori, 680-8553 Japan (e-mail: ykita@muses.tottori-u.ac.jp).

best appropriate for integer or discrete variables. Applying TS for hard continuous variables problems is quite tough and time consuming. Therefore, a set of continuous variables, which is a set of pipe segment lengths, has better determined by other flexible heuristic algorithm and GA is chosen for this study. Furthermore, we propose the application of a GA in the TS for the optimal values of parameters required in the search that has much effect to the performance of the search and are difficult to define.

The basic form of TS is founded on ideas originally proposed by Fred Glover in 1986. The method is known as an effective meta-heuristic algorithm that guides a local heuristic search procedure to explore the solution space beyond local optimality and attempt to locate the global optimum. A distinguishing feature of TS is represented in its iterative improvement framework that exploits adaptive forms of memory to help diversity the search and avoid becoming in local optima. The overall approach of TS is to avoid trapping in cycling by forbidding or penalizing moves which take the solution, in the next iteration, to points in the solution space previously visited (hence "tabu").

GAs are search algorithms based on the mechanics of natural selection and natural genetics (Goldberg [12]). GAs use a vocabulary borrowed from natural genetics; perform a multi-directional search by maintaining a population of potential solutions while all other methods process a single point of the search space.

TS has been found to be very effective to a variety of hard combinatorial problems such as scheduling, location and allocation, traveling salesman problem etc. Nevertheless, TS is quite a new technique for water resources problems as well as water distribution pipe network problems while the applications of GAs to the problems of water distribution network have been found from many works (e.g., Simpson et al. [24]; Dandy et al. [5]; Savic and Walters [23]; Montesinos et al. [19]). Application of TS to the water distribution pipe network optimization has been found in the work of Cunha and Ribeiro [4].

The effectiveness of the proposed combination approach is assessed through application to the three well-known test networks taken from the literature: the two-loop network, the Hanoi network, and the New York City network. The solutions obtained from the present work are compared to those obtained from SA in the work of Tospornsampan et al. [27]. The solutions obtained are compared with those published in literature using both conventional methods and heuristic methods as well.

II. Design of Water Distribution Pipe Network

Pipe network problems are usually solved by numerical methods using a computer since any analytical solution requires the use of many simultaneous equations. Three simple methods used to solve pipe network problems are the Hardy Cross method, the linear theory method, and the Newton Raphson method. The Hardy Cross method that involves a series of successive approximations and corrections to flows in individual pipes is the most popular procedure of analysis. Besides, the most well-known formulas that are used to evaluate the head loss in pipes are Darcy-Weisbach equation and Hazen-Williams equation. The Hazen-Williams equation that has been widely used in water supply engineering is written as:

$$h_f = \alpha L (Q/C)^{1.852} D^{-4.87} \quad (1)$$

where h_f is the head loss, α is a numerical conversion constant whose numerical value depends on the used units, L is the length of the pipe, Q is the discharge, C is a Hazen-Williams coefficient of roughness and D is the pipe diameter.

The optimal design of a water distribution network for gravity system is to find the combination of commercial pipes with different sizes and lengths that provides the minimum cost for the given layout of network and a set of specified demands at the nodes while the pressure heads required at the nodes are also satisfied. Consider the network that composed of N nodes, t links, and m loops; the objective function of the least-cost design is to minimize the total cost of the system which is often assumed to be a cost function of pipe diameters and lengths as:

$$F = \min \sum_{i \in t} \sum_{j \in p(i)} C_{i,j} x_{i,j} \quad (2)$$

where F is the total cost of the network system, $C_{i,j}$ is the cost of the unit length of the jth pipe segment in link i which can be deterministic value or calculated by empirical formulas, $x_{i,j}$ is the length of the jth pipe segment in link i, and $p(i)$ is the set of all pipe segments in link i.

The objective function above is subject to the following constraints:

1. the flow entering a junction or node must equal the flow leaving it (the law of continuity):

$$\sum_{i \in in(k)} Q_i - \sum_{i \in out(k)} Q_i = q_k \quad \forall k \in N \quad (3)$$

where Q_i is the flow in link i, $q_{,k}$ is the demand at node k, $in(k)$ and $out(k)$ are the sets of all links connected into and out of node k, respectively. Note that $q_k > 0$ if k is a demand node, and $q_k < 0$ if k is a supply node.

2. The algebraic sum of the head losses (pressure drops) around any closed loop must be zero:

$$\sum_{i \in loop(n)} \pm hf_i = 0 \quad \forall n \in m \quad (4)$$

where hf_i is the head loss in link i which is calculated from (1), and $loop(n)$ is the set of all links in the nth loop

3. The head at a certain node in the network must satisfy a given minimum and maximum head limitations:

$$H_k^{\max} \geq H_k = H_s + \sum_{i \in path(s,k)} \pm hf_i \geq H_k^{\min} \quad \forall k \in N \qquad (5)$$

where $H_k^{\max}$ and $H_k^{\min}$ are the maximum and minimum head allowed at node k, respectively, H_k is the head at node k, H_s is the head at any starting node s, and path(s,k) is the path of links that connecting node s with node k.

4. Minimum and Maximum diameter requirements may be specified for certain pipes in the network:

$$D_{\max} \geq D_{i,j} \geq D_{\min} \quad \forall i, j \qquad (6)$$

where $D_{i,j}$ is the diameter of the jth pipe segment in link i, D_{max} and D_{min} are the upper and lower bounds for diameter of pipes.

5. Minimum required discharge might be specified for certain pipes in the network:

$$Q_i \geq Q_i^{\min} \quad \forall i \qquad (7)$$

where $Q_i^{\min}$ is the minimum required flow rate along link i.

6. The total length of pipe segments in link i must be equal to the length of the link and each length must be nonnegative value:

$$\sum_{j \in p(i)} x_{i,j} = L_i \quad \forall i, j \qquad (8)$$

$$L_i \geq x_{i,j} \geq 0 \quad \forall i, j \qquad (9)$$

where L_i is the length of link i.

III. TABU SEARCH

The essential feature of TS is an effective use of the adaptive memory. The memory can be either short term or long term. A short-term memory stores the record of the most recent move (transition from solution to solution) history and is used to prevent the search cycling in those recently visited solutions. A long-term memory is based on the record of the whole move history. It is used to guide the search of neighbours of elite solutions (named as intensification search strategy), or not explored but promising regions (named as diversification search strategy). Simple TS only employs the short-term memory. Advanced TS uses both short-term and long-term memory. In this work a simple TS that only employs the short-term memory is considered.

The basic principle of TS is to prevent cycling by maintaining a list of recent moves. This list is referred to as a tabu list. The tabu list is used to prevent cycling of a move as forbidden, i.e., “Tabu”. Each time a move is made, it is placed on a list. When considering a move, it becomes unchoosable, or tabu, if it is on the tabu-list. There are many different ways to form a tabu list. The choice of an appropriate type of tabu list depends on the type of problem and the algorithm being used. One or several tabu lists can be created for a problem.

In a tabu list, old moves are typically removed from the list after some number of iterations depending on the length of the tabu list (or the tabu tenure in the original word). Each move is recorded in a list according to their orders in which they are made. Each time a new element is added to the bottom of a list, the oldest element on the list is dropped from the top. The size or the length of the list is an important parameter. The length of the list can be fixed or varied over different intervals of time or stages of the search. If the length of the list is too small, cycling may not be prevented. Conversely a too long size creates too many restrictions that may not improve the search but spend an unnecessary computational time. It is difficult to find an appropriate value that prevents cycling and does not excessively restrict the search. The length of the tabu list is a critical parameter in most TS algorithms.

When a move, which is considered to be tabu, is found to be better than the best solution found so far, it can be selected as a move. This criterion is called an aspiration criterion in the tabu search literature. Aspiration criterion is taken to determine when tabu activation can be overridden in order to avoid missing good solutions. In this work a simple type of aspiration criterion is adopted that consisting of removing a tabu classification form a move when the move yields a solution better than the best obtained so far.

A search can be terminated either when a maximum number of iterations is reached or when a convergence is achieved. The general procedure of the TS described in this section is summarized in Table 1.

TABLE I
TABU SEARCH PROCEDURE

Step 1	Assume an initial configuration S_i. Initialize the tabu list length parameter and aspiration criterion. Set the tabu list empty. Set the optimal configuration $S_o = S_i$.
Step 2	Generate a candidate list or a set of neighbors of the current configuration.
Step 3	Evaluate the fitness values of all candidates.
Step 4	Sort all candidates according to their fitness values in the descending order.
Step 5	Fine the best configuration S_j that is not TABU or is satisfied the aspiration criterion. Set the current configuration $S_i = S_j$. IF S_i is better than S_o then $S_o = S_i$.
Step 6	Update the tabu list and the aspiration criterion.
Step 7	Repeat Step 2 to Step 6 until a stopping criterion is satisfied.

IV. GENETIC ALGORITHM

GAs initially start from randomly generating a population of strings (also referred to as chromosome), each string is composed of a series of substrings (bits or genes in other words) representing components or decision variables that are related or used to evaluate the fitness of the problem through the objective function. One string has its own fitness value obtained from objective function and is one solution for the problem. The entire population of such strings represents a generation. A string can be represented by binary code, gray code or real code (or floating point in other words). The binary and gray representations traditionally used in GAs have some drawbacks when applied to multidimensional, high-precision numerical problems, that is, the length of the binary solution vector becomes very long for such problem. This, in turn, generates an excessive large search space that results in poor performance of GAs.

The initial population undergoes a series of genetic operators resulting a new population with new fitness values in each string, which is the initial population for next generation. A simple GA consists of three basic operators: selection or reproduction, crossover, and mutation. Selection is a process in which individual strings are copied according to their fitness values. A string with a higher value has a higher probability of contributing one or more offspring in the next operation.

After selection, a crossover operator partially exchanges some bits between a random mated pair of selected strings from the mating pool, results in two new offspring that preserve the best material from their two parent strings which are expected to have a better fitness values than both of their parent strings. The number of swapping strings is approximately designed by probability of crossover (P_c).

Mutation is the occasional random alteration of the value of a string position, performs on a bit-by-bit basis with small probability (P_m) equal to the mutation rate. When mutation is used sparingly with selection and crossover, it is an insurance policy against premature loss of important notions. The mutation operator plays a secondary role in the simple GA.

The algorithm is repeated successively for many generations till the stopping criterion is satisfied. The stopping criterion of a GA is determined by either a specific number of generations or a convergence to a single solution where the change in the fitness values is insignificant.

Good performance of the GA as suggested by many researchers (dandy et al. [5]) may be obtained using high crossover probability (0.5 to 1.0) and low mutation probability (0.001 to 0.05). In this paper the probability of crossover ranges from 0.7-0.8 and the probability of mutation approximately equal to one to three bit per string length on average are used. The basic principle of GAs with review of their application can be found from the work of Goldberg [12] and Michalewicz [18].

V. Optimal Design of Water Distribution Network Problem using the Combined TS-GA GAs

The optimal design of pipe network problem can be classified into three categories. A continuous diameter design is an optimal set of pipe diameters that may take only continuous real values. A discrete diameter design is a set of pipe diameters that are selected from a specified set of commercial pipe sizes that span an entire length of the links. A split-pipe design may be derived from a continuous diameter design by decomposing a length of continuous diameter into two segment lengths of the two adjacent commercial diameters to create two pipes that span the link. Anyhow, the continuous diameter design is not practical because commercial pipe diameters are available in specified discrete diameters. Although attempts have been made to convert continuous diameters into one or two commercial discrete diameters in a segment, it is found that the conversion may not guarantee the optimality or even the feasibility of the solution.

The new procedure for the split-pipe design in which a set of pipe diameters are selected from a specified set of commercial pipe sizes has been proposed by Tospornsampan et al. [27] using the simulated annealing (SA). The least cost solutions obtained from that work were the lowest-cost solutions for all test networks to which it was applied. However, there is no proof that those solutions are the global optimal solutions. Therefore, the combination of TS and GA is proposed in this study. It is expected that further improvements may be achieved from the combination approach.

The proposed algorithm of the combined TS–GA for the split-pipe design of water distribution network problem consists of five major steps as summarized in Table 2. The details of the combination algorithm are described as follows.

TABLE II
COMBINED TS-GA PROCEDURE

Step 1	Assume initial sets of pipe segment diameters and pipe segment lengths.
Step 2	Determine the optimal set of pipe segment diameters by the TS algorithm using an initial set of pipe segment diameters obtained from step 1 as an initial configuration and an initial set of pipe segment lengths obtained from step 1 as a set of constant variables.
Step 3	Determine the optimal set of pipe segment lengths by the GA using the optimal set of pipe segment diameters obtained from the TS as a set of constant variables.
Step 4	Use the optimal set of pipe segment lengths obtained from GA as a set of constant variables and the optimal set of pipe segment diameters previously obtained from the TS as an initial configuration to determine the optimal set of pipe segment diameters again by the TS algorithm.
Step 5	Repeat Step 3 and 4 until a stopping criterion is satisfied.

A. *Initial configuration*

The initial configuration of the water distribution network problem is a set of decision variables of the problem, which is a combination of commercial pipe segments in a network. In contrast to other researchers, we found that an initial configuration need not be a feasible solution. As a penalty function is used to decrease the fitness of an infeasible candidate, a fitter candidate will has a higher priority to be selected. As algorithm proceeds, an inferior configuration will be removed subsequently. We found that an initial configuration where each pipe has a low commercial diameter size is likely effective. Nevertheless, a configuration where each pipes has the lowest commercial diameter size is ineffective.

In the split-pipe design, an initial configuration for the TS algorithm in step 2 and 4 as written in Table 2 is composed of two commercial pipe diameters in each links. The total number of decision variables is then two times of the total number of links. The initial configuration for the GA in step 3 as written in Table 2 is composed of a segment length in each link. Because two pipe segments are concatenated to form a link, a length of the remaining segment is derived by subtracting a segment length to the entire length of the link. The total number of decision variables is then equal to the number of links. The decision variables of pipe diameters for the TS algorithm are discrete values but the decision variables of pipe lengths for the GA are continuous values whose required precision are decided at two decimal places.

B. Candidate List for TS (Neighborhood structure)

During the search, the current neighborhood is explored, and a suitable move is selected. Ideally, all promising solutions should be evaluated but for large neighborhoods this may not be feasible. Instead, the search may be terminated as soon as a good move is found (Thesen [25]). Therefore a part of the entire neighborhood is explored by a neighborhood generation mechanism. This mechanism defines a list of candidate solutions to be chosen in each iteration. The mechanism used to generate neighborhood structures varies with problem behavior. In this study a candidate solution consists of all segment pipes having the same diameter as in the current configuration except one that has the bigger diameter size or the smaller diameter size.

C. Tabu list and the length of the tabu list

The information of a move being stored in the tabu list describes the location and the diameter of a pipe segment that distinguish the move from its current configuration.

The tabu list length parameter has much influence to the performance of TS algorithm. The wrong choices of the parameter may mislead to an inefficient algorithm. There are no standard rules for the choice of the appropriate list length for a specific problem. Many researchers have given some guidelines to decide the tabu list length. Anyhow, the efficient list length depends on the type of problem being solved and the algorithm being used. We found that effects of a list length to distinct initial configurations are different. On the other hand, different list lengths provide different solutions when apply to the same initial configuration.

In this study a GA is applied in the TS for the optimal values of list length parameters. Different fixed values of list length parameters are randomly generated by GA within the predefined range. It is found from trial and error that the effective range of parameters is within four times of the number of pipes. Each parameter derived after decoding from the same generation is evaluated by the TS algorithm using the same initial configuration. Each time after a TS algorithm is terminated for each parameter, the best set of pipe segment diameters found so far is stored. In this sub GA process, the binary coding representation, tournament selection, two-point crossover, and simple mutation (all are referred to in Michalewicz [18]) are adopted.

D. Genetic Algorithm for pipe segment lengths

The best set of pipe segment diameters obtained from the TS becomes a set of constant variables for the next GA process in order to find the optimal set of pipe segment lengths which is a set of decision variables in the GA. The real coding representation, modified ranking selection (referred to in Tospornsampan et al. [26]), uniform crossover (referred to in Michalewicz [18]), and non-uniform mutation (referred to in Michalewicz [18]) are adopted. The algorithm is carried out until the maximum number of generations is reached. The optimal set of pipe segment lengths is used as a set of constant variables and the previous optimal set of pipe diameters obtained from the last TS algorithm becomes an initial configuration in the next TS algorithm.

Note that for the original discrete diameter design in which only a single pipe is chosen for a link, this process of the GA is unnecessary because a set of pipe segment lengths is needed not to be determined.

VI. ILLUSTRATED EXAMPLES (MODEL APPLICATION)

The performance of the combined TS-GA approach for the least cost design of water distribution network is evaluated through applications to the three well-known networks: the two-loop network, the Hanoi network, and the New York city water supply network.

Following the work of Tospornsampan et al. [27], three different values of α are adopted in the present work as well. These three parameter values consist of the maximum and minimum values of α covering the range of published values (according to the work of Savic and Walters [23]) which are equal to 10.5088 and 10.9031 respectively for Q in m^3/h, and D in centimeters (= 8.439×10^5, and 8.710×10^5 respectively for Q in ft^3/s, and D in inches), and another values of α which are the same values as used in the original works of each problem.

Both of discrete diameter design and split-pipe design are to be derived. The original discrete diameter design is called the single pipe design hereinafter because both designs are derived from discrete variables in this study.

A. Two-Loop Network

The two-loop network, as shown in Fig. 1, was first introduced by Alperovits and Sharmir [1]. The network consists of eight pipes, seven nodes, and two loops. The network is fed by gravity from a constant head reservoir at the first node. The system is to supply water to meet the required demand and to satisfy minimum pressure head at each node.

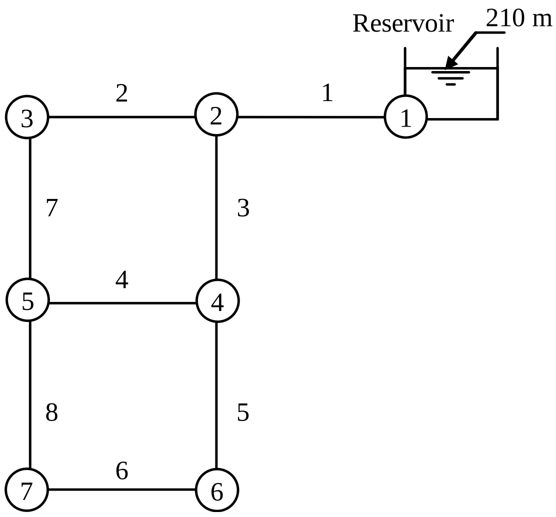

Fig. 1 Two-Loop Network

TABLE III
PREVIOUS SOLUTIONS OF TWO-LOOP NETWORK

Authors	Fitting α^a	Cost (units)	Solution
Alperovits and Shamir (1997)	10.9031	479,525.00	Split-pipe
Goulter et al. (1986)	10.9031	435,015.00	Split-pipe
Kessler and Shamir (1989)	10.6792	417,500.00	Split-pipe
Eiger et al. (1994)	10.5088	402,352.06	Split-pipe
Loganathan et al. (1995)	10.6792	403,657.00	Split-pipe
Savic and Walters (1997)	10.5088	419,000.00	Single
Savic and Walters (1997)	10.9031	420,000.00	Single
Cunha and Sousa (1999)	10.5088	419,000.00	Single
Cunha and Ribeiro (2004)	10.5088	419,000.00	Single
Tospornsampan et al. (200*)	10.5088	419,000.00	Single
Tospornsampan et al. (200*)	10.9031	419,000.00	Single
Tospornsampan et al. (200*)	10.5088	400,337.97	Split-pipe
Tospornsampan et al. (200*)	10.6792	403,751.22	Split-pipe
Tospornsampan et al. (200*)	10.9031	408,035.00	Split-pipe

[a] For Q in m^3/h, and D in centimeters

TABLE IV
SOLUTIONS OF TWO-LOOP NETWORK FROM COMBINED TS-GA

Link	TS-GA1 α^a=10.5088		TS-GA2 α^a=10.6792		TS-GA3 α^a=10.9031	
	D (in.)	L (m)	D (in.)	D (in.)	D (in.)	L (m)
1	18	1000	18	1000	20	50
					18	950
2	12	170.05	10	793.23	12	237.96
	10	829.95	12	206.77	10	762.04
3	16	1000	16	1000	16	1000
4	1	1000	1	1000	1	1000
5	14	395.87	16	693.47	16	756.28
	16	604.13	14	306.53	14	243.72
6	10	1000	10	1000	10	1000
7	8	107.85	8	97.91	8	85.35
	10	892.15	10	902.09	10	914.65
8	1	1000	1	1000	1	1000
Cost (units)	400,214.16		403,644.78		408,203.53	

[a] For Q in m^3/h, and D in centimeters

Fourteen sizes of commercial pipe are available for the network and each of them has its own unit cost. The Harzen-Williams coefficient is fixed at 130 for all pipes. The basic data necessary for the optimization are given in the paper of Alperovits and Sharmir [1].

TABLE V
OPTIMAL PRESSURE HEADS FOR TWO-LOOP NETWORK

Link	Min. Head Req. (m)	TS-GA1 α^a=10.5088 Head (m)	TS-GA2 α^a=10.6792 Head (m)	TS-GA3 α^a=10.9031 Head (m)
2	30	53.35	53.24	53.24
3	30	30.00	30.00	30.00
4	30	44.03	43.85	43.75
5	30	30.00	30.00	30.00
6	30	30.00	30.00	30.00
7	30	30.18	30.10	30.00

[a] For Q in m^3/h, and D in centimeters

Table 3 shows the solutions of the two-loop network published in literature. Only solutions of the single pipe design and split-pipe design are presented, as solutions of continuous diameter design are not practicable in reality. The best solutions obtained from the TS-GA are shown in Table 4. The optimal pressure heads corresponding to those solutions are shown in Table 5. The optimal solutions of the single pipe design obtained from the present study are not published herein as they are the same as those presented in the work of Tospornsampan et al. [27].

The solutions obtained using α = 10.5088 and α = 10.6792 are found to have lower costs than those presented in the work of Tospornsampan et al. [27] while the best solution obtained using the upper limit of α = 10.9031 is little inferior. The least cost solution thus found in this study becomes the lowest-cost solution for the two-loop network to date.

B. Hanoi Network

The water distribution trunk network in Hanoi, Vietnam, was first introduced by Fujiwara and Khang [8]. The configuration of the network is shown in Fig. 2. The network consists of 34 pipes, 32 nodes, and 3 loops. The problem is similar to the two-loop network that the network is fed by gravity from a single fixed head source and is to satisfy demands at required pressures. In this problem six sizes of commercial pipe are available and the cost of each pipe *i* with diameter D_i and length L_i is calculated from $C_i = 1.1 \times D_i^{1.5} \times L_i$ in which cost is in dollars, diameter is in meters, and length is in meters. The Harzen-Williams coefficient is fixed at 130 for all pipes. The data necessary for the optimization can be found in the work of Fujiwara and Khang [8].

It is found from published solutions in the literature that the solutions of this problem are sometimes less realistic because some segments of split-pipes have too short lengths compared with their link lengths. To avoid such problem, a constraint of the minimum length of pipe segment length that must be at least or more than 5% of its link length is imposed to this network.

Because the network in this problem is larger and more complex than the two-loop network, the numbers of iterations required for the TS process and the number of generations

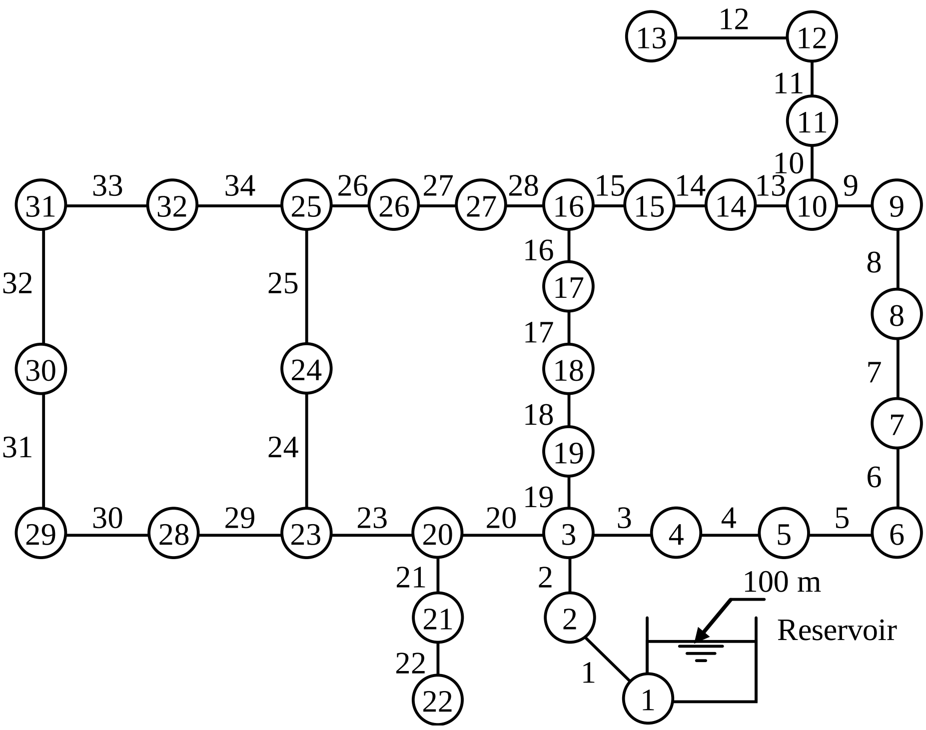

Fig. 2 Hanoi Network

TABLE VI
PREVIOUS SOLUTIONS OF HANOI NETWORK

Authors	Fitting α[a]	Cost ($ million)	Solution
Fujiwara and Khang (1990, 1991)	10.5088	6.320	Split-pipe
Sonak and Bhave (1993)	10.5088	6.046	Split-pipe
Eiger et al. (1994)	10.5088	6.027	Split-pipe
Savic and Walters (1997)	10.5088	6.073	Single
Savic and Walters (1997)	10.9031	6.195	Single
Cunha and Sousa (1999)	10.5088	6.056	Single
Cunha and Ribeiro (2004)	10.5088	6.056	Single
Tospornsampan et al. (200*)	10.5088	6.026	Single
Tospornsampan et al. (200*)	10.9031	6.188	Single
Tospornsampan et al. (200*)	10.5088	6.023	Split-pipe
Tospornsampan et al. (200*)	10.6823	6.111	Split-pipe
Tospornsampan et al. (200*)	10.9031	6.200	Split-pipe

[a] For Q in m^3/h, and D in centimeters

required for the GA process are both higher than those used in the two-loop network. Table 6 shows the solutions of the network published in the literature. The best solutions of the split-pipe design obtained from the TS-GA are shown in Table 7 and the optimal pressure heads corresponding to those solutions are shown in Table 8. The optimal solution of the single pipe design obtained using the lower limit of α = 10.5088 is the same as that presented in the work of Tospornsampan et al. [27] while the solution obtained using the upper limit of α = 10.9031 is superior. The lowest cost value derived in this study using the upper limit of α = 10.9031 is cheaper than that obtained in the work of Tospornsampan et al. [27] about 0.08%. The difference of the present solution from that of Tospornsampan et al. [27] is found in link 11, 13, 14, 15, 17, 19, 26, 27, 30 and 33 where their pipe diameters are 24, 16, 12, 12, 20, 24, 24, 12, 16 and 16, respectively.

Although the minimum length constraint is imposed, the TS-GA provides very remarkable solutions. All solutions obtained using different values of α are superior to those obtained by the SA in the work of Tospornsampan et al. [27] and they are superior to other corresponding solutions published in the literature. The comparison of those solutions shows that the TS-GA has produced significant improvements and the least cost solution obtained in this study becomes the lowest-cost solution yet presented in the literature for this problem. The TS-GA provides more consistent results than the SA. The results obtained from the TS-GA are not so much different from each other in cost values, though the TS-GA spent little more computation time.

C. *New York City Water Supply Network*

The configuration of the New York City water supply network is shown in Fig. 3. The data of the New York City water supply tunnels is taken from Quindry et al. [21], Fujiwara and Khang [8] and Dandy et al. [5]. The network consists of 21 pipes, 20 nodes, and 2 loops. The work is to construct additional gravity flow tunnels parallel to the existing system to satisfy the increased demands at the required pressures. Sixteen sizes of diameters (including none pipe) are available and the cost of each pipe i with diameter D_i and length L_i is calculated from $C_i = 1.1 \times D_i^{1.24} \times L_i$ in which cost is in dollars, diameter is in inches, and length is in feet. Although the cost function is used to calculate the investment cost for this problem, the unit cost of each pipe has

TABLE VII
SOLUTIONS OF HANOI NETWORK FROM COMBINED TS-GA

Link	TS-GA1 α^a=10.5088		TS-GA2 α^a=10.6823		TS-GA3 α^a=10.9031	
	D(in.)	L (m)	D(in.)	D(in.)	D(in.)	L (m)
1	40	100	40	100	40	100
2	40	1350	40	1350	40	1350
3	40	900	40	900	40	900
4	40	1150	40	1150	40	1150
5	40	1450	40	1450	40	1450
6	40	450	40	450	40	450
7	40	850	40	850	40	850
8	40	850	40	805.28	40	850
			30	44.72		
9	40	150.61	40	800	40	800
	30	649.39				
10	30	950	30	950	30	950
11	24	1200	24	1200	24	498.99
					30	701.01
12	24	3000	24	3000	24	3000
13	20	68.48	20	800	20	800
	16	731.52				
14	12	115.65	12	240.87	16	500
	16	384.35	16	259.13		
15	12	550	12	550	12	550
16	12	2730	12	2730	12	2730
17	16	1750	16	1750	16	1750
18	24	800	20	436.95	24	800
			24	363.05		
19	24	281.99	24	400	24	400
	20	118.01				
20	40	2200	40	2200	40	2200
21	16	577.74	16	525.2	20	1122.27
	20	922.26	20	974.8	16	377.73
22	16	33.7	16	66.8	12	500
	12	466.3	12	433.2		
23	40	2650	40	2650	40	2650
24	30	1230	30	1230	30	1230
25	30	1300	30	1300	30	1300
26	20	850	20	850	20	850
27	16	300	16	42.9	16	300
			12	257.1		
28	12	750	12	750	12	750
29	16	1500	16	1500	16	1500
30	12	2000	12	1579.26	12	2000
			16	420.74		
31	12	1600	12	1600	12	1600
32	16	150	16	150	16	93
					20	57
33	16	860	16	860	20	860
34	24	950	24	897.68	24	950
			20	52.32		
Cost ($Million)	5.995		6.066		6.152	

[a] For Q in m^3/h, and D in centimeters

TABLE VIII
OPTIMAL PRESSURE HEADS FOR HANOI NETWORK

Link	Min. Head Req. (m)	TS-GA1 α^a=10.5088	TS-GA2 α^a=10.6823	TS-GA3 α^a=10.9031
		Head (m)	Head (m)	Head (m)
1	100	100.00	100.00	100.00
2	30	97.18	97.14	97.08
3	30	62.24	61.61	60.82
4	30	57.77	56.91	55.99
5	30	52.23	51.08	50.01
6	30	46.42	44.93	43.71
7	30	45.07	43.49	42.23
8	30	43.48	41.79	40.47
9	30	42.23	40.21	39.07
10	30	39.06	39.21	38.04
11	30	37.52	37.64	36.45
12	30	34.14	34.21	34.30
13	30	30.00	30.00	30.00
14	30	31.80	35.80	34.45
15	30	30.39	32.00	32.77
16	30	30.05	30.26	30.71
17	30	34.64	32.73	34.37
18	30	52.91	49.60	52.53
19	30	58.26	58.88	57.97
20	30	50.99	50.44	49.55
21	30	34.82	34.65	35.27
22	30	30.00	30.00	30.00
23	30	44.70	44.26	43.35
24	30	38.81	38.60	37.61
25	30	34.95	34.95	33.92
26	30	30.57	31.09	30.27
27	30	30.07	30.00	30.05
28	30	39.07	38.32	37.98
29	30	30.00	30.00	30.00
30	30	30.21	30.12	30.51
31	30	30.48	30.38	30.74
32	30	32.86	32.69	31.66

[a] For Q in m^3/h, and D in centimeters

been transformed into discrete values and is given in Dandy et al. [5]. In the present work, the discrete values of unit costs are used. The Harzen-Williams coefficient for this problem is assumed at 100 for all existing and new pipes.

Previous solutions of the New York City water supply network published in literature are shown in Table 9. The lowest cost design published in literature was found in the work of Fujiwara and Khang [8]. Unfortunately their solution was proved to be clearly infeasible (Loganathan et al. [16]; Dandy et al. [5]; Savic and Walters [23]). Therefore, the feasible lowest cost solution of this problem is that of Savic and Walters [23] which is derived from the discrete diameter design.

The best solutions obtained from the TS-GA are shown in Table 10. The optimal pressure heads corresponding to those solutions are shown in Table 11. The best solutions of the single diameter obtained from this work are not published herein also as they are the same as those published in the work of Tospornsampan et al. [27]. The best solution obtained from using lower limit of α = 843900 is little more expensive than that obtained from the SA in the work of Tospornsampan et al. [27] while the best solution obtained from using α = 851500 and α = 871000 are almost same.

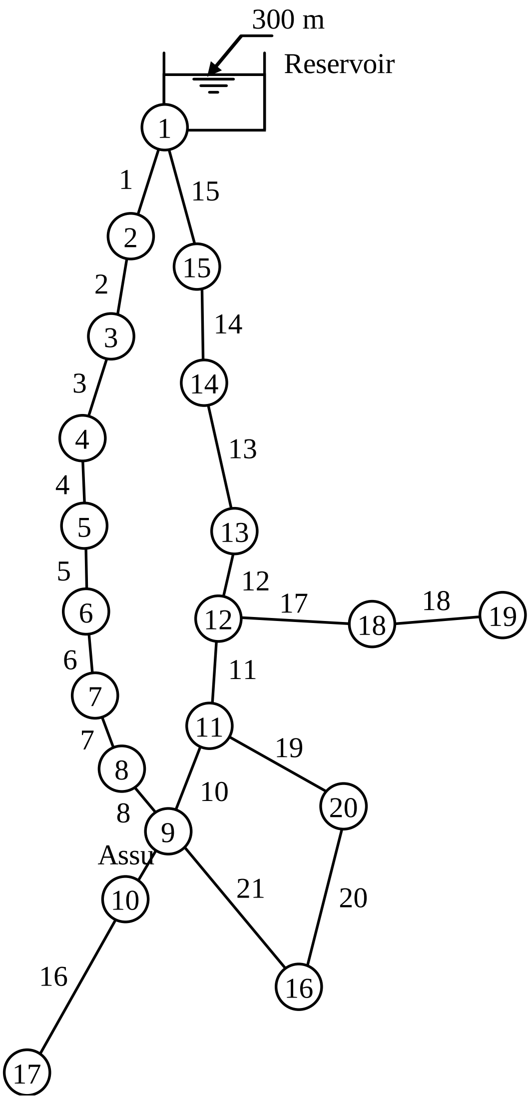

Fig.3 New York City Water Network

TABLE IX
PREVIOUS SOLUTIONS OF NEW YORK CITY WATER NETWORK

Authors	Fitting α^a	Cost ($ million)	Solution
Morgan and Goulter (1985)	851500	38.90	Split-pipe
Morgan and Goulter (1985)	851500	39.20	Single
Fujiwara and Khang (1990)	none	36.60[b]	Split-pipe
Loganathan et al. (1995)	851500	38.04[c]	Split-pipe
Dandy et al. (1996)	851500	38.80	Single
Savic and Walters (1997)	843900	37.13	Single
Savic and Walters (1997)	871000	40.42	Single
Montesinos et al. (1999)	851500	38.80	Single
Cunha and Ribeiro (2004)	843900	37.13	Single
Tospornsampan et al. (200*)	843900	37.13	Single
Tospornsampan et al. (200*)	871000	40.42	Single
Tospornsampan et al. (200*)	843900	36.87	Split-pipe
Tospornsampan et al. (200*)	851500	38.05	Split-pipe
Tospornsampan et al. (200*)	871000	40.04	Split-pipe

1/ for Q in ft^3/s, and D in inches
[b] Infeasible
[c] Slightly infeasible

TABLE X
SOLUTIONS OF NEW YORK CITY WATER NETWORK FROM COMBINED TS-GA

Link	TS-GA1 α^a=843900		TS-GA2 α^a=851500		TS-GA3 α^a=871000	
	D (in.)	L (ft)	D (in.)	D (in.)	D (in.)	L (ft)
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	96	4102.6	132	7251.82	0	0
	108	5497.4	120	2348.18		
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0	0	0	0	0
15	0	0	0	0	132	5493.94
					144	10006.06
16	96	26400	108	444.6	84	26400
			96	25955.4		
17	96	31200	96	30815.37	96	31200
			108	384.63		
18	72	767.3	84	23940.9	84	22641.69
	84	23232.7	72	59.1	72	1358.31
19	72	14400	72	14205.46	72	14400
			84	194.54		
20	0	0	0	0	0	0
21	72	26400	72	26400	60	721
					72	25679
Cost ($Million.)	36.89		38.05		40.04	

[a] For Q in ft^3/s, and D in inches

VII. CONCLUDING REMARKS

The combination of two heuristic-based: TS and GA has been developed to obtain the least cost of the split-pipe design of water distribution network. The combination algorithm has been applied to the three well-known networks appearing in literature: the two-loop network, the Hanoi network, and the New York City water network.

The TS-GA provides very satisfactory and high quality solutions. The lowest-cost solutions of the two-loop network and the Hanoi network yet presented in literature are found in this study. Most of solutions obtained from the TS-GA are superior to those obtained from the SA in the work of Tospornsampan et al. [27] and they are superior to most of solutions published in the literature. Performance of the

TABLE XI
OPTIMAL PRESSURE HEADS FOR NEW YORK CITY WATER SUPPLY NETWORK

Link	Min. Head Req. (ft)	TS-GA1 α^a=843900 Head (ft)	TS-GA2 α^a=851500 Head (ft)	TS-GA3 α^a=871000 Head (ft)
1	300	300.00	300.00	300.00
2	255	294.35	294.24	294.58
3	255	286.50	286.24	287.11
4	255	284.21	283.89	284.95
5	255	282.18	281.82	283.07
6	255	280.61	280.21	281.64
7	255	278.15	277.67	279.46
8	255	276.43	276.55	276.35
9	255	273.70	273.71	274.20
10	255	273.67	273.68	274.17
11	255	273.80	273.80	274.35
12	255	275.10	275.08	275.86
13	255	278.07	278.06	279.17
14	255	285.55	285.54	287.40
15	255	293.33	293.32	295.91
16	260	260.10	260.00	260.00
17	272.8	272.80	272.80	272.80
18	255	261.24	261.16	261.56
19	255	255.00	255.00	255.00
20	255	260.76	260.68	260.79

[a] For *Q* in ft^3/s, and *D* in inches

combination algorithm is better than the SA for the design problem of water distribution network. A number of good solutions are obtained by the TS-GA more than the SA.

Although the realistic design required the single pipe solution, but if this is done, the design will not be optimal. It is proved from both of the work presented by Tospornsampan et al. [27] and from the present work that the least cost solutions obtained from the split-pipe design always provide lower costs than those obtained from the single pipe design. A split-pipe design can be an alternative for a network where the lowest investment cost is really needed.

The convergence of the solutions of the split-pipe design obtained from the TS-GA is not clear. A number of runs were repeated many times to obtain the convergent solutions. Anyhow we decided to stop the algorithm after we found that only marginal differences in the costs can be obtained, compared with the best solution obtained so far. Because global optimal solutions related to the least cost design of water distribution networks are not known and there is no proof about global optimality, because the heuristic-based algorithm is used, it is expected that the better solutions still can be obtained in future if the research will continue again.

It is found that the performance of TS is largely dependent on fine-tuning of the parameters as well as the neighborhood generation mechanism. Different parameters and neighborhood generation mechanisms have different influences to the performance of the algorithm and the solution being obtained. The use of GA in the search for the parameters of the TS algorithm implemented in this study seems to work well. Anyhow, more effective guidelines to derive an appropriate parameter and more robust generation mechanism that can improve the performance of the algorithm are to be further considered.

The concept of the combined TS-GA developed in this study is just another idea of combination way of heuristic based techniques. We hope that it may contribute some useful benefits (guidelines) in diverse problems. The proposed algorithm is expected to be an efficient alternative to further applications of the design, layout and operation of water distribution network related problem as well.

A concept of TS is rather simple but implementation of the technique to a specific problem is quite complex. Complexity is not only present in the problems but in the technique itself. Further improvement of the technique to enhance its strengths and compensate its weaknesses is expected. Since TS is quite new technique for water resources problems, extensive applications of the technique to this area of researches are also expected.

REFERENCES

[1] E. Alperovits and U. Shamir, Design of optimal water distribution systems, *Water Resources Research*, vol. 13, no. 6, pp. 885-900, 1997.

[2] P.R. Bhave and V.V. Sonak, A critical study of the linear programming gradient method for optimal design of water supply networks, *Water Resources Research*, vol. 28, no. 6, pp. 1577-1584, 1992.

[3] M.D.C. Cunha and J. Sousa, Water Distribution Network Design Optimization: Simulated Annealing Approach, *Journal of Water Resources Planning and Management ASCE*, vol. 125, no. 4, pp. 215-221, 1999.

[4] M.D.C. Cunha and L. Ribeiro, Tabu search algorithms for water network optimization, *European Journal of Operational Research*, vol. 157, pp. 746-758, 2004.

[5] G.C. Dandy, A.R. Simpson, and L.J. Murphy, An improved genetic algorithm for pipe network optimization, *Water Resources Research*, vol. 32, no. 2, pp. 449-458, 1996.

[6] G. Eiger, U. Shamir, and A.B. Tal, Optimal design of water distribution networks, *Water Resources Research*, vol. 30, no. 9, pp. 2637-2646, 1994.

[7] O. Fujiwara, B. Jenchaimahakoon, and N.C.P. Edirisinghe, A modified linear programming gradient method for optimal design of looped water distribution networks, *Water Resources Research*, vol. 23, no. 6, pp. 977-982, 1987.

[8] O. Fujiwara and D.B. Khang, A two-phase decomposition method for optimal design of looped water distribution networks, *Water Resources Research*, vol. 26, no. 4, pp. 539-549, 1990.

[9] O. Fujiwara and D.B. Khang, Correction to "A two-phase decomposition method for optimal design of looped water distribution networks" by Okitsugu Fujiwara and Do Ba Khang, *Water Resources Research*, vol. 27, no. 5, pp. 985-986, 1991.

[10] F. Glover, J.P. Kelly, M. Laguna, Genetic algorithms and tabu search: hybrids for optimization, Computers Operations Research 22(1) (1995) 111-134.

[11] F. Glover and M. Laguna, *Tabu Search*, Kluwer Academic Publishers, Dordrecht, 1997.

[12] D.E. Goldberg, *Genetic Algorithms in Search, Optimization, and Machine Learning*, 2nd edn. Addison-Wesley, Reading, Mass, 1989.

[13] I.C. Goulter, B.M. Lussier, and D.R. Morgan, Implications of head loss path choice in the optimization of water distribution networks, *Water Resources Research*, vol. 22, no. 5, pp. 819-822, 1986.

[14] A. Kessler and U. Shamir, Analysis of the linear programming gradient method for optimal design of water supply networks, *Water Resources Research*, vol. 25, no. 7, pp. 1469-1480, 1989.

[15] S. Kirkpatrick, C.D. Gelatt, and M.P. Vecchi, Optimization by Simulated Annealing, *Science*, vol. 220, no. 4598, pp. 671-680, 1983.

[16] G.V. Loganathan, J.J. Greene, and T.J. Ahn, Design heuristic for globally minimum cost water-distribution systems, *Journal of Water Resources Planning and Management ASCE*, vol. 121, no. 2, pp. 182-192, 1995.

[17] A.H. Mantawy, S.A. Soliman, and M.E. El-Hawary, The long-term hydro-scheduling problem – a new algorithm, *Electric Power Systems Research*, vol. 64, pp. 67-72, 2003.

[18] Z. Michalewicz, *Genetic Algorithms + Data Structures = Evolutionary Programs*, 3rd edn. Springer-Verlag, New York, 1996.
[19] P. Montesinos, A.G. Guzman, and J.L. Ayuso, Water distribution network optimization using a modified genetic algorithm, *Water Resources Research*, vol. 35, no. 11, pp. 3467-3473, 1999.
[20] D.R. Morgan and I.D. Goulter, Optimal urban water distribution design, *Water Resources Research*, vol. 21, no. 5, pp. 642-652, 1985.
[21] G.E. Quindry, E.D. Brill, and J.C. Liebman, Optimization of looped water distribution systems, *Journal of the Environmental Engineering Division ASCE*, vol. 107, no. 4, pp. 665-679, 1981.
[22] G.E. Quindry, E.D. Brill, J.C. Liebman, and A.R. Robinson, Comment on 'Design of optimal water distribution systems' by E. Alperovits and U. Shamir, *Water Resources Research*, vol.15, no. 6, pp. 1651-1654, 1979.
[23] D.A. Savic and G.A. Walters, Genetic algorithms for least-cost design of water distribution networks, *Journal of Water Resources Planning and Management ASCE*, vol. 123, no. 2, pp. 67-77, 1997.
[24] A.R. Simpson, G.C. Dandy, and L.J. Murphy, Genetic algorithms compared to other techniques for pipe optimization, *Journal of Water Resources Planning and Management ASCE*, vol. 120, no. 4, pp. 423-443, 1994.
[25] A. Thesen, Design and evaluation of tabu search algorithms for multiprocessor scheduling, *Journal of Heuristics*, vol. 4, pp. 141-160, 1998.
[26] J. Tospornsampan, I. Kita, M. Ishii, Y. Kitamura, Optimization of Multiple Reservoir System Operation Using Combination of Genetic Algorithm and Discrete Differential Dynamic Programming, A Case Study in Mae Klong System, Thailand, Journal of the International Society of Paddy and Water Environment Engineering 3(1) (2005) 29-38.
[27] J. Tospornsampan, I. Kita, M. Ishii, Y. Kitamura, Split-Pipe Design of Water Distribution Networks Using Simulated Annealing, (Submitted for publication to WASET together with this manuscript).
[28] K.V.K. Varma, S. Narasimhan, and M. Bhallamudi, Optimal design of water distribution systems using an NLP method, *Journal of Environmental Engineering ASCE*, vol. 123, no. 4, pp. 381-388, 1997.
[29] C. Zheng, P. Wang, Parameter structure identification using tabu search and simulated annealing, *Advances in Water Resources*, vol. 19, no. 4, pp. 215-224, 1996.