A NOVEL APPROACH FOR OPTIMAL DESIGN OF WATER DISTRIBUTION NETWORKS

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SUMMARY

A water distribution network consists of pipes, reservoirs, pumps, tanks, and other hydraulic components. The main purpose of a water distribution network is to provide reliable service to the individual customers in the required quantity and at sufficient pressure. Nearly 80% to 85% of the cost of a water supply project is used in the distribution network; therefore, using reasonable methods for designing a water distribution system will result in considerable savings. In this paper, we introduce a novel simulation-based optimization method, CMAESEP, which couples the Covariance Matrix Adaptation Evolution Strategy Optimization Algorithm and the Epanet hydraulic simulator for optimal designing water distribution networks. The proposed method is applied to the published benchmark water network of Hanoi. The result shows that the new method is able to identify the best solution and is promising method for a further development of the design of complex water distribution network.

Keywords: Epanet, optimal design, simulation-based optimization, water distribution network.

I. INTRODUCTION

A typical water distribution network (WDN) generally consists of four major, interconnected components which represent the zones in which the components operate, namely, (i) Sources of water: reservoirs, rivers, wells, wastewater treatment plants, and so on; (ii) Interconnected pipes that carry water between sources and water users; (iii) Pumps used to feed water into the network; and (iv) Tanks. Due to numerous advantages, water distribution networks (WDN) have become remarkably competitive as one of the most important infrastructures in urban and regional economic development for delivering water from sources to consumers with both sufficient discharge and pressure requirements [1].

An adequate network layout, the selection of components and the dimensioning of the distribution system are amongst the major challenges when setting up a water distribution network. Calculating the hydraulic properties for each network configuration is commonly considered as "the balancing" between flows, head losses, velocities and pressures. Accordingly, there are also critical problems with regard to design task of a WDN. WDN design is a multidisciplinary task solving both technical and economical issues [6]. For each WDN configuration, solving technical problems commonly means the consideration of hydraulic conditions while the economic issues mentioned here may involve capital, construction, and operation costs. A successfully designed WDN requires a balance between these two issues; therefore, an appreciate approach for designing a WDN plays a significant role.

Traditional methods using trial and error approach try to minimize cost by reducing the design parameters (such as pipe diameters, network layout) while satisfying all pre-defined requirements (for example, required nodal head, flow velocity, water quantity). Several methods used very often are Hardy Cross method (proposed 1936), Newton-Raphson method (proposed 1963), Linear Theory method (1972), and Gradient method (1987). In fact, these approaches are very time consuming and depend mainly on designer's experiment.

To overcome the restrictions of trial and error approach, many studies try to develop optimization techniques for solving WDN design problems. At the beginning of WDN design optimization, several possible determined techniques can be considered such as dynamic programming – DP (Liang, 1971), linear programming – LP (Alperovits and Shamir, 1977), and non-linear programming – NLP (Lansey and Mays, 1989). The techniques commonly require numerous simplifying assumptions and are suitable for basic PWDNs with a limited number of pipes. Also, they are time consuming even for small design problems [8]. Furthermore, they often fail (or reach just local optimum) in offering solutions with respect to problems with a large number of decision variables and non-linear objective functions [7]. Therefore, it is difficult to completely solve complex problems of WDN design optimization with these techniques.

From the beginning of 1990's methodologies have focused on stochastic optimization techniques (or meta–heuristic optimizations). Some stochastic techniques have received much attention in WDN optimization, such as Genetic Algorithms – Gas (Simpson et al., 1994); Ant Colony Optimization Algorithm – ACOA (Maier et al., 2003); Simulated Annealing Optimization – SAO (Cunha & Sousa, 1999); Shuffled Complex Evolution –SCE (Liong et al., 2004); harmony search - HS (Geem et al., 2006); Particle Swarm Optimization – PSO (Suribabu & Neelakantan, 2006); differential evolution – DE (Suribabu, 2010). Generally, when searching for an optimal solution with a stochastic optimization, the objective function is evaluated for a set of solutions of decision variables (for example, pipe diameters in a WDN pipe-size optimization problem). Based only on the objective function of the previous solutions, new and better-oriented values of decision variables would be generated [2, 7].

In recent years, a novel method, namely simulation-based optimization, which couples an optimization technique with a computer simulation model, has been widely developed and applied in many real-world engineering design problems in general, as well as in WDN optimization problems in particular. With the continuing developments in computer technology, simulation-based optimization is receiving increasing attention as a helpful decision-making tool.

In this paper, we present the ability of a new simulation-based optimization, CMAESEP, which couples the "Covariance Matrix Adaptation Evolution Strategy Optimization Algorithm - CMAES" and a hydraulic simulator - Epanet for optimal designing water distribution networks by comparing the results achieved in advance with a benchmark published network - Hanoi network proposed by Fujiwara and Khang [4].

II. METHODOLOGY

2.1. Formulation of the optimal WDN design problem

The overall design problem of a WDN optimization can be stated mathematically in terms of the nodal heads H and the various design variables D as follows [1, 6, 8]:

Objective:

$$min\,PIC = min\sum_{i=1}^{np} f_1\left(D_i, L_i\right) \qquad (1)$$

Where PIC is initially capital cost for pipes, f_1 is an appropriate cost function of pipe diameter (D_i) and length (L_i). np is the number of pipes in the network.

Subject to:

- *Conservation of mass (continuity equation)*: The continuity equation at a node ensures that the flows entering are equal to the flows leaving that node. Hence, the continuity equation at each node $j, j = 1, 2,...,nn$ (*nn*: number of nodes in the WDN) may be written as:

$$\sum_{connected\,to\,j} Q_{j\_in} = \sum_{connected\,to\,j} Q_{j\_out} + q_j^{req} \qquad (2)$$

where Q_{j_in} and Q_{j_out} are the flows in and out connected to node j directly, and q_j^{req} is the required demand at node j

- *Conservation of energy:*

The difference in energy between two points must be equal to the summation of major and minor head losses and the energy added or extracted between these points (Eq. 3):

$$E_1 + \sum h_m = E_2 + \sum h_{L1-2} \qquad (3)$$

Where Enegy

$$E = Z + \frac{p}{\gamma} + \frac{V^2}{2g} \qquad (4)$$

$Z, \frac{p}{\gamma}, \frac{V^2}{2g}$ are the elevation head (potential energy), pressure head, and velocity head, respectively

$\sum h_{L1-2}$ is the total head loss in the pipe caused by major and minor losses between two points (1) and (2);

h_m is the head added by pump.

- Decision variables constraints

$$D_i \in D \qquad (5)$$

D is the given set of commercially available pipe diameters which are are mass-produced in standard sizes.

- Nodal head bounds

$$H_j^{min} \leq H_j < H_i^{max} \qquad (6)$$

H^{min} *and* H^{max} are permitted minimum and maximum nodal heads at node, respectively. These limits are often given requirement for each node. The lower bound is likely related to required outlet equipment, whereas the upper bound may be for maintaining structural integrity or for maximum working pressure of pipe material.

2.2. Structure of new method

Structure of the proposed simulation-based optimization approach, CMAESEP, is built as in Figure 1. The model consists of two main components: (1) The optimization module using Covariance Matrix Adaptation Evolution Strategy Algorithm for evaluating objective functions and constraints and (2) The Epanet simulator for addressing laws of conservation mass and energy.

The principle of the proposed approach can be interpreted as in the following procedure:

** Pre-processing:*

(1) Define optimization problems including decision variables (for instant, pipe diameters), objective function (cost), and given constraints (limits of nodal pressures, flow velocities)

(2) Set up an Epanet performance for the WDN to be analyzed using an arbitrary set of decision variables on which the objective function depends directly and other given hydraulic properties. A set of big values for the decision variables would be preferred in order to ensure that the network can perform normally. Epanet solves the hydraulic equation system of conservation of mass and energy and consequently provides flows, pressures, velocities, and other characteristics as outputs.

(3) Create the analyzed result under the specific form of standard Epanet input file (*.inp) that is consistent with the structure required in Epanet.

(4) Create initial settings for model such as normalized initial decision variables, standard deviations, model parameters, model criteria, and other given data.

(5) Set up an appropriate interface

** Interface*

(6) Formulate the objective function (i.e. cost minimization or network reliability maximization), constraints and other given parameters in interface module.

(7) The CMAES optimization mode starts with a set of initially normalized compatible decision variables which receive the values within interval [0 1]. The continuous parameters produced by CMAES must be transformed to discrete values by rouding each of them to the nearest normalized availabe pipe diamete. This set is then denormalized and transferred to Epanet.

(8) The toolkit loads the Epanet input file to obtain a description of the network to be analyzed and must close itself down once all analyses are completed. At this time, all parameters that define the design and operation of the WDN being analyzed are retrieved and set by using other specific toolkit function such as the function for node, pipe, pattern, option, etc.

(9) The description of the WDN characteristics including flow rates, head losses, velocities in pipes, piezometric nodal head (also nodal pressure) at nodes and so on is then

transferred back to the interface module.

(10) Check the user-predefined constraints.

(11) Calculate the objective function for current iteration with the assigned decision variables regarding current network configuration.

(12) If there is any violation of the constraints occurring in any iteration, penalty functions will be added to the objective function.

(13) Based on the comparison of two objective function values i.e. the previous objective function value and the current one, optimization mode valuates a new set of initial decision variables which would be adjusted to move to better values for the next iteration.

(14) Steps (6) - (12) above are repeated until a criterion is met.

* *Post-processing*

(15) Minimum cost corresponding to an smallest pipe diameter set is produced when the model stops.

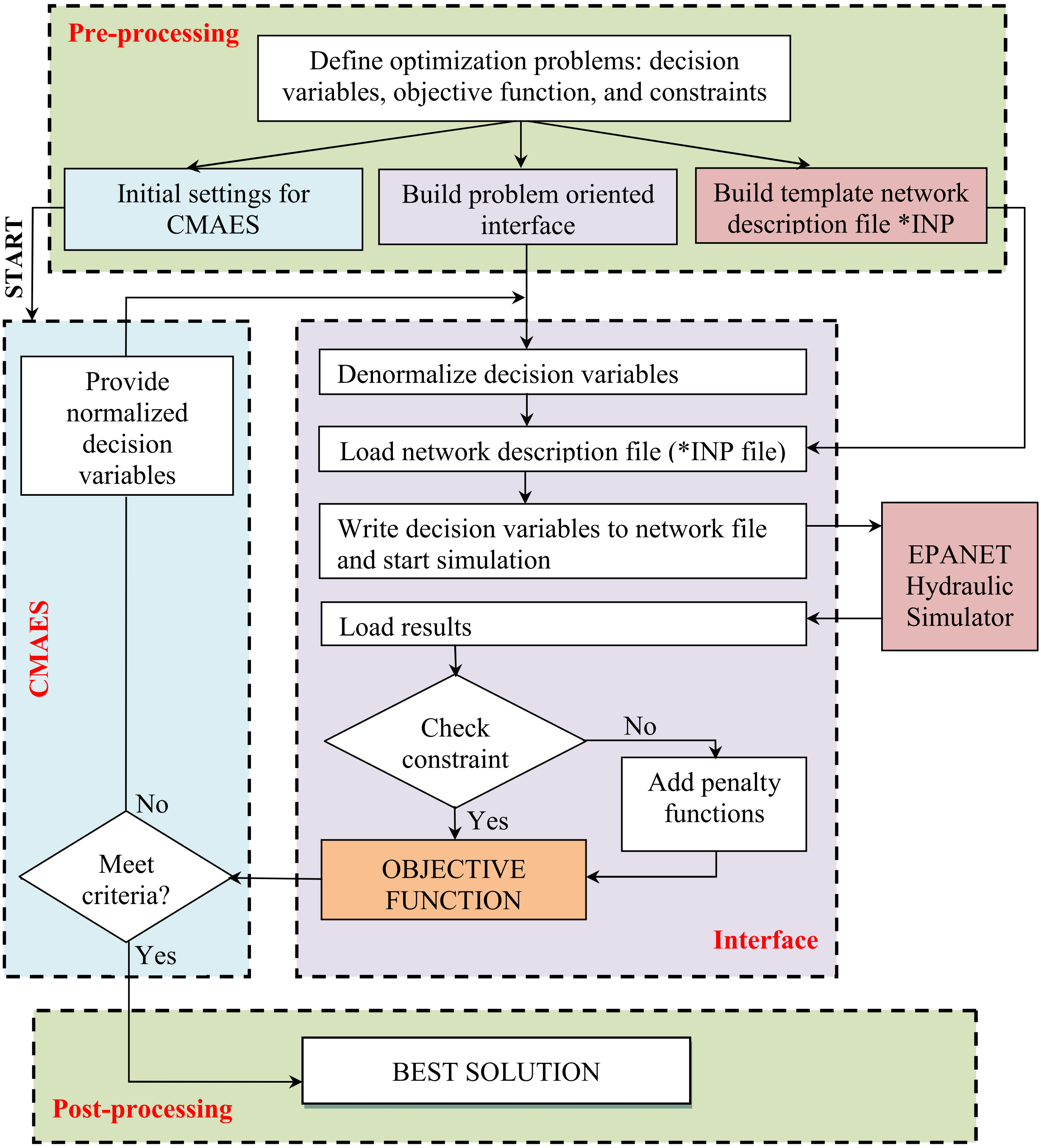

Figure 1. Structure of the proposed simulation-based optimization CMA-ES-EP

2.3. Epanet and its toolkit

Epanet, a hydraulic models proposed by Rossman (2000), is based on the Gradient Method introduced by Todini and Pilati (1988). By using Epanet, it is clearly recognized that conservation equations of mass and energy are always satisfied. Epanet provides a fully equipped and extended period simulation which consists of a series of steady-state flows caused by any change in water demand, water level in reservoir and tank, and so on. Therefore, Epanet can immediately demonstrate the hydraulic properties at any node and pipe at a specific period of time. Epanet can also express the results of analyses under various convenient types such as table and graph. Particularly, contents of the standard Epanet input data file (*.inp file), which describes the network being simulated, can be analyzed, interpreted, and stored in a sharable memory area and can be assessed by a specific tool. This file can either be created external Epanet or by Epanet itself (figure 2).

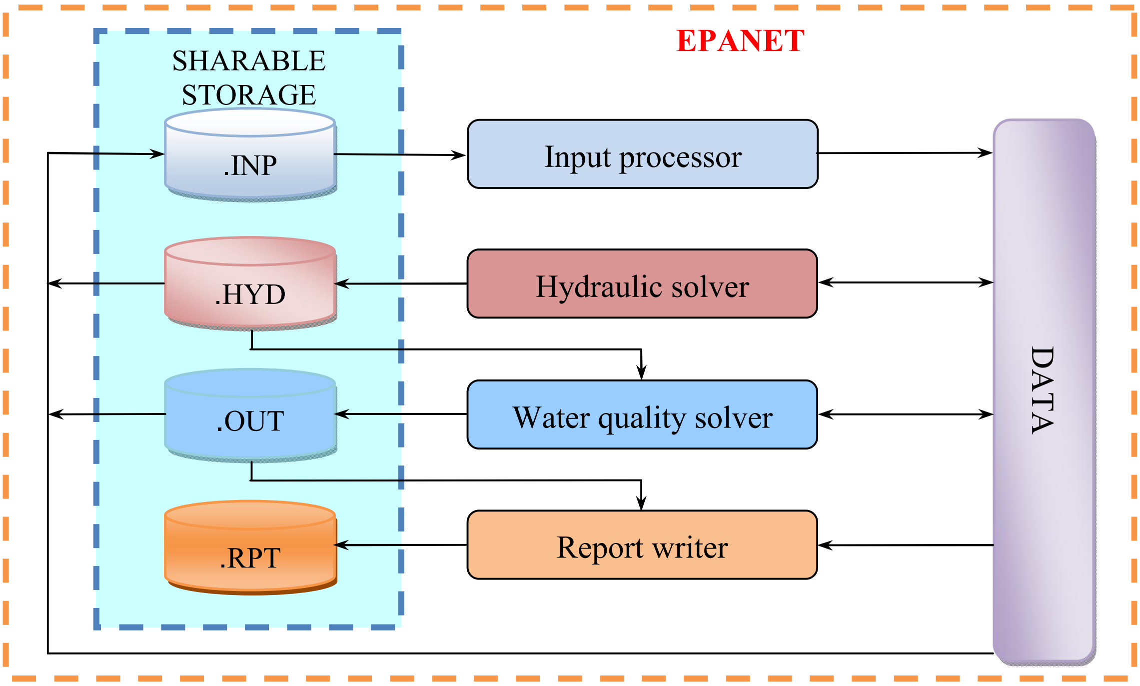

Figure 2. Outline of the Epanet capability (derived from Rossman, 2000)

The Epanet toolkit (Eliades, 2009) is a dynamic link library (DLL) of functions which permits designers to connect Epanet with a programming language that can call these functions for example C++, Visual Basic, Matlab, etc... These functions can retrieve and set all characteristics of a water network described in a suitable format file (*.inp file) and write results in an output file as well. The toolkit is useful for optimization or automated calibration application that requires network analysis.

2.4. Covariance matrix adaptation evolution strategy algorithm (CMAES)

CMAES was introduced by Hansen [3] based on the normally distributed mutative steps to survey search space while adjusting its mutation distribution to produce likely successful steps in the future from the current search. Theoretically, CMAES utilizes two basic design principles, namely, invariance and un-biased of the variation of object and strategy parameters. Invariance characteristics cause compatibility classes of objective functions and therefore allow for generalization of empirical results. The algorithm includes four major procedures and can be described briefly in figure 3.

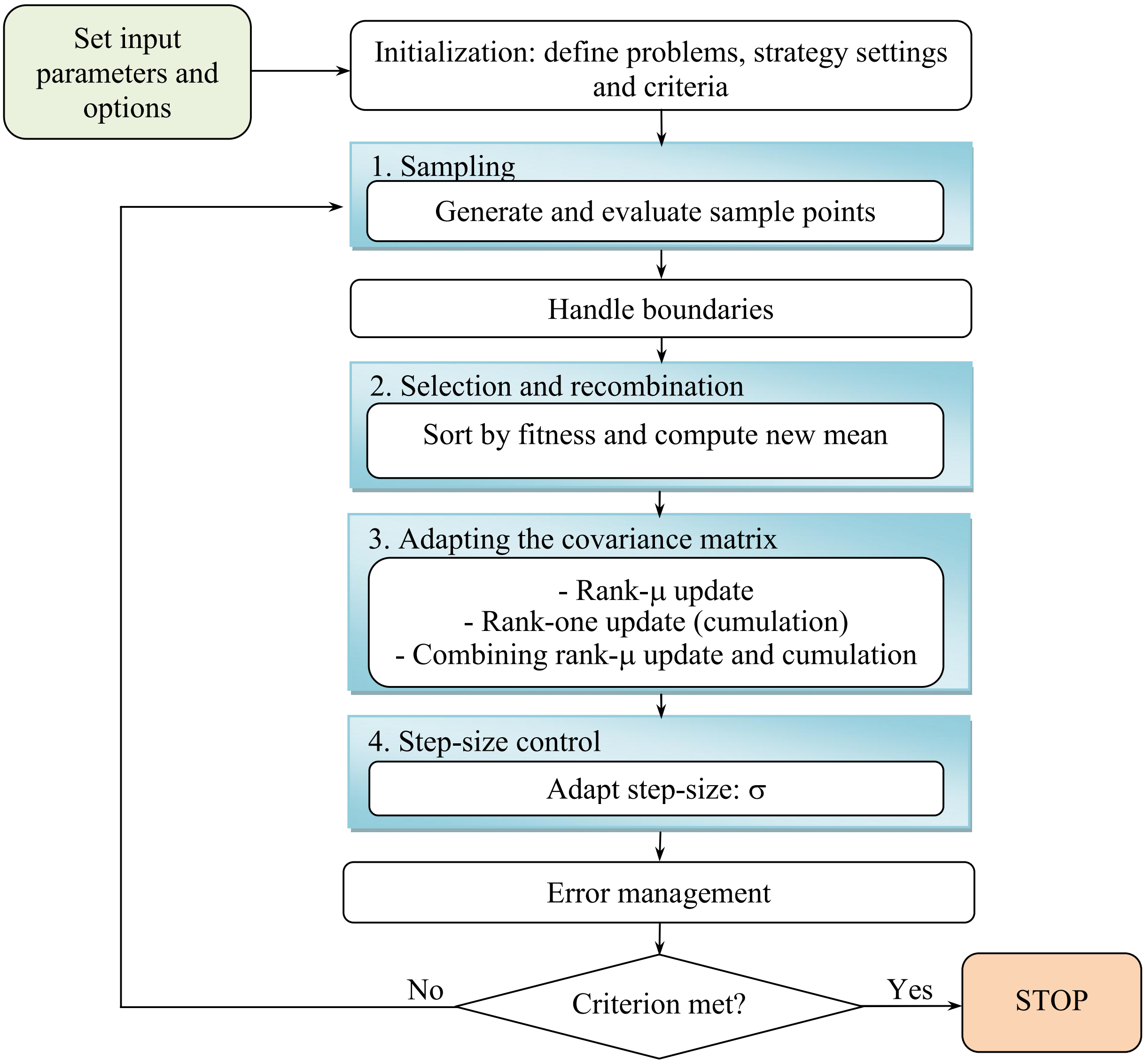

Figure 3. General CMAES procedure flow chart

III. RESULTS (Application to the case study of the hanoi water distribution network)

The Hanoi water network introduced by Fujiwara and Khang [4] consists of 34 pipes, 31 demand nodes (at an elevation of 0 m), and 3 loops which is supplied by a single fixed head source (Reservoir No.1) at an elevation of 100 m (figure 4).

Decision variables are the diameters of 34 pipes which have to be chosen from a specified set of 6 different values [304.8, 406.4, 508, 609.6, 762, and 1016]. Thus, there is a total of 6^{34} ($2.87*10^{26}$) possible combinations of pipe diameters for this network. The nodal characteristics are depicted in table 1 and nodal minimum required pressure is determined to be 30m. This network was studied by many other researchers afterwards such as Savic and Walters (1997), Abebe and Solomatine (1998), Cunha and Sousa (1999), Liong et al. (2004), Geem (2006) [2, 6].

By doing sensitivity analysis, selected CMAESEP parameters include: population size *popsize* = *floor(40*log(N)* with N is number of pipes in the network, ii) initially normalized decision variables: $x_{ini} = 0.7$, and iii) standard deviations: $\sigma_x = 0.4$. Penalty function $C_{pen} = n.C_{max}$, in which n is number of nodes failing the constrain (6) and C_{max} is the cost of the most expensive network.

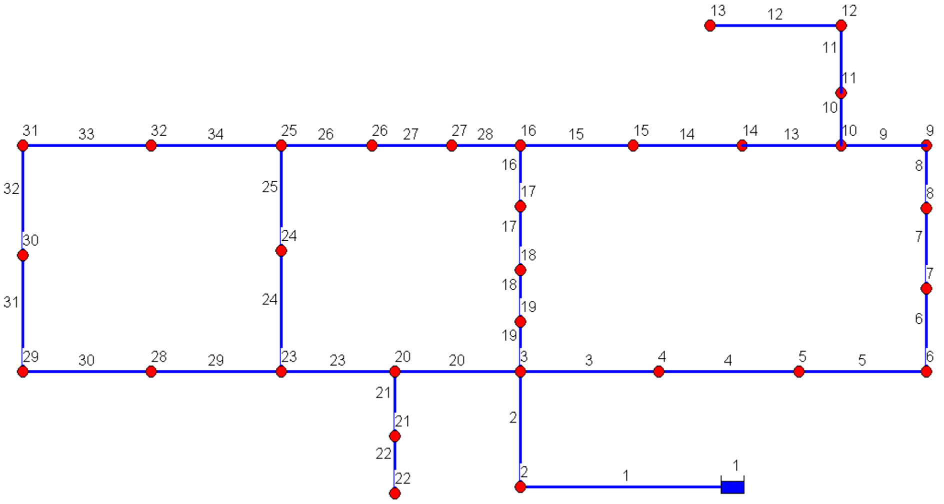

Figure 4. Hanoi water network layout representing nodes and pipes

Table 1. Nodal characteristics

Node ID	Demand (m^3/hr)	Required Pressure	Node ID	Demand (m^3/hr)	Required Pressure	Node ID	Demand (m^3/hr)	Required Pressure
1	-19616	---	12	560	30	23	1045	30
2	890	30	13	940	30	24	820	30
3	850	30	14	615	30	25	170	30
4	130	30	15	280	30	26	900	30
5	725	30	16	310	30	27	370	30
6	1005	30	17	865	30	28	290	30
7	1350	30	18	1345	30	29	36	30
8	550	30	19	60	30	30	360	30
9	525	30	20	1275	30	31	105	30
10	525	30	21	930	30	32	805	30
11	500	30	22	485	30	---	---	---

Through the visible convergence process, in the optimization process, several normalized decision variables exceeded the interval [0 1] at around the first 5,000 iterations. However, the box constraint handling method built in CMAES adjusted these infeasible decision variables to feasible ones at subsequent iterations as shown in figure 5.

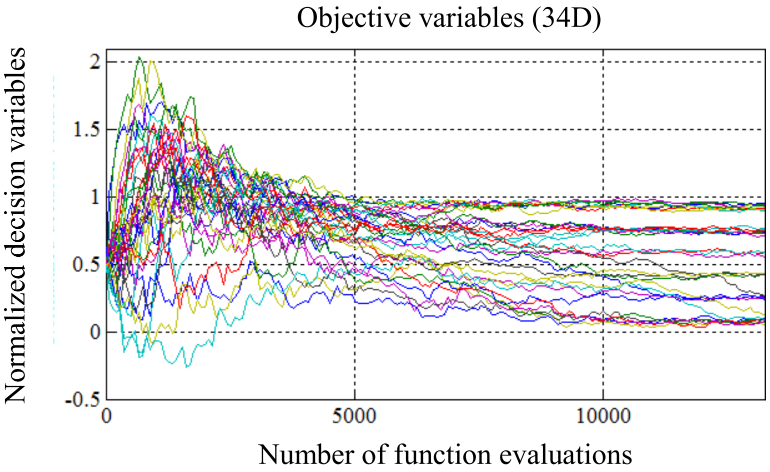

Figure 5. The convergence of decision variables of Hanoi water network design optimization

The smallest pipe diameter set produced by CMAESEP is presented in Column 8, Table 2. Accordingly table 2, the best result has been obtained compared to the previous solutions with a relatively low number of function evaluations (12,800 – can be seen in figure 5). The smallest surplus head of + 0.17 m at node 13 yielded by this optimal solution showed that all nodal pressure are satisfied the given requirements.

Table 2. Comparison of the best solutions of pipe diameters (mm), corresponding costs (Mi.$), NFEs and minimum surplus head achieved by previous studies and the current

Pipe ID	**Pipe Diameters (mm)**						
	Fujiwara and Khang (1990)	**Savic &Walters (1997)**	**Abebe & Solomatine (1998)**	**Cunha & Sousa (1999)**	**Liong et al. (2004)**	**Geem (2006)**	**Current Study**
	NLP	***GA***	***GA***	***SAO***	***SCE***	***HS***	***CMAESEP***
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1	1016	1016	1016	1016	1016	1016	1016
2	1016	1016	1016	1016	1016	1016	1016
3	1016	1016	1016	1016	1016	1016	1016
4	1016	1016	1016	1016	1016	1016	1016
5	1016	1016	762	1016	1016	1016	1016
6	1016	1016	1016	1016	1016	1016	1016
7	969.26	1016	1016	1016	1016	1016	762
8	933.20	1016	762	1016	762	1016	762
9	897.38	1016	762	1016	762	1016	762
10	739.90	762	762	762	762	762	762
11	671.83	609.6	762	609.6	762	609.6	762
12	590.55	609.6	762	609.6	609.6	609.6	609.6
13	497.08	508	406.4	508	406.4	508	304.8
14	396.75	406.4	609.6	406.4	304.8	406.4	406.4
15	304.80	304.8	762	304.8	304.8	304.8	406.4
16	571.50	304.8	762	304.8	609.6	304.8	508
17	641.10	406.4	762	406.4	762	406.4	609.6
18	736.85	508	1016	508	762	508	762
19	743.71	508	1016	508	762	508	762
20	979.93	1016	1016	1016	1016	1016	1016
21	440.94	508	508	508	508	508	508
22	321.31	304.8	508	304.8	304.8	304.8	304.8
23	827.78	1016	762	1016	762	1016	1016
24	560.32	762	406.4	762	762	762	762
25	465.84	762	508	762	609.6	762	609.6
26	304.80	508	304.8	508	304.8	508	406.4
27	565.66	304.8	609.6	304.8	508	304.8	304.8
28	624.08	304.8	508	304.8	609.6	304.8	304.8
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*

Pipe ID	**Pipe Diameters (mm)**						
	Fujiwara and Khang (1990)	**Savic &Walters (1997)**	**Abebe & Solomatine (1998)**	**Cunha & Sousa (1999)**	**Liong et al. (2004)**	**Geem (2006)**	**Current Study**
	NLP	***GA***	***GA***	***SAO***	***SCE***	***HS***	***CMAESEP***
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
29	540.766	406.4	609.6	406.4	406.4	406.4	406.4
30	491.236	406.4	762	304.8	406.4	304.8	304.8
31	419.608	304.8	762	304.8	304.8	304.8	304.8
32	304.8	304.8	762	406.4	406.4	406.4	304.8
33	304.8	406.4	762	406.4	508	406.4	304.8
34	569.722	508	304.8	609.6	609.6	609.6	508
Cost	**6.320**	**6.073**	**7**	**6.056**	**6.22**	**6.056**	**6.046**
NFEs	\	\	16,910	53,000	25,402	200,000	**12,800**
Minimum surplus head (m)	+1.05	+1.16	+0.13	+1.15	+0.05	+1.15	**+0.17**

IV. CONCLUSIONS

In this paper, we propose a novel model, called CMAESEP, which couples the Covariance Matrix Adaptation Evolution Strategy (CMAES) optimization algorithm with the Epanet hydraulic simulator for optimal designing water distribution networks. In this model, initially capital cost is considered as objective function while satisfying all the conditions of sufficient nodal demands and required nodal pressures.

The model is applied to the Hanoi water distribution network in order to verify its capacity in finding the minimum set of pipe diameters. In fact, the solution produced by the proposed method is the best result compared to the previous ones with an acceptable number of function evaluations. It can be stated that the application of CMAESEP to problems related to the design of water distribution networks seems to have a promising future.

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PHƯƠNG PHÁP TIẾP CẬN MỚI TRONG THIẾT KẾ TỐI ƯU MẠNG LƯỚI PHÂN PHỐI NƯỚC

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TÓM TẮT

Một mạng lưới phân phối nước bao gồm các đường ống, bể chứa, bơm, đài nước và một số thiết bị khác với nhiệm vụ chính là phải đảm bảo dịch vụ cung cấp nước tin cậy, đáp ứng đủ cả về lượng và cột áp yêu cầu tới các khách hàng dùng nước. Chi phí xây dựng mạng lưới phân phối nước thường chiếm 80 - 85% tổng chi phí xây dựng một dự án cấp nước, do đó sử dụng phương pháp hợp lý thiết kế mạng lưới phân phối nước sẽ tiết kiệm đáng kể chi phí. Trong bài báo này, chúng tôi giới thiệu phương pháp tối ưu dựa mô phỏng, CMAESEP, là sự kết hợp giữa thuật toán tối ưu Chiến lược tiến hóa thích nghi ma trận hiệp phương sai và mô hình thủy lực Epanet. Mô hình mới được áp dụng với mạng phân phối nước chuẩn mẫu. Kết quả áp dụng cho thấy mô hình có thể đưa ra giải pháp tốt nhất và có triển vọng trong thiết kế các mạng lưới phân phối nước phức tap.

Từ khóa: Epanet, mạng lưới phân phối nước, thiết kế tối ưu, tối ưu dựa mô phỏng.

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