Research Article

Cost Optimization of Hanoi Water Distribution Network with Meta-Heuristic Optimization Algorithms

Hanoi Su Dağıtım Şebekesinin Meta-Sezgisel Optimizasyon Algoritmaları ile Maliyet Optimizasyonu

Volkan Yilmaz[1], Meral Buyukyildiz[1], Omer Kaan Baykan[2]

[1]*Konya Technical University, Faculty of Engineering and Natural Sciences, Civil Engineering Department, Konya*
vyilmaz@ktun.edu.tr (0000-0002-5407-860X), mbuyukyildiz@ktun.edu.tr (0000-0003-1426-3314)
[2]*Konya Technical University, Faculty of Engineering and Natural Sciences,Computer Engineering Department, Konya*
okbaykan@ktun.edu.tr (0000-0001-5890-510X)
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Abstract

Water transfer and distribution systems have high-cost values in a process from the collection of required water to the delivery by end-users. Besides the existence of few options for water transmission systems, there are more possible solutions for water distribution systems which have to require necessary conditions. Defining the best system which has minimum cost value for a water distribution system has been an optimization problem in time. Different optimization algorithms have been revealed with the help of the innovation of computer technologies and these algorithms were used in cost optimization of water distribution network field and performance of algorithms have been evaluated nearly for 50 years. In this study, Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) methods, commonly used in the literature, and recently revealed Artificial Bee Colony (ABC) algorithm method were applied to Hanoi water distribution network for the purpose of cost optimization. To determine the best performing algorithm for this case study; the comparative performance analysis of convergence velocity, stability, and distribution of results were evaluated.
Keywords: *Optimization, water distribution network, artificial bee colony, genetic algorithm, particle swarm optimization algorithm*

Öz

Gerekli suyun toplanmasından kullanıcılara ulaştırılmasına kadar geçen bir süreç içerisinde su iletim ve dağıtım sistemlerinin yüksek maliyet değerleri içerdiği görülmektedir. Su iletim sistemlerinde daha az sayıda seçeneğin bulunmasına karşılık su dağıtım şebekeleri istenen şartları sağlayan daha fazla olası çözümü içermektedir. Zamanla, minimum maliyet değerine sahip olan en iyi sistemin tasarlanması bir optimizasyon problemi haline gelmiştir. Son 50 yıldır bilgisayar teknolojilerindeki gelişme ile birlikte çeşitli optimizason algoritmaları ortaya atılmış ve bu algoritmalar su dağıtım şebekelerinin maliyet optimizasyonu konusunda kullanılarak algoritmaların performansları değerlendirilmiştir. Bu çalışmada literatürde yaygın olarak kullanılmış olan Parçacık Sürü Optimizasyon ve Genetik Algoritma yöntemlerine ilave olarak diğer iki yönteme kıyasla daha yakın zamanda ortaya atılmış olan Yapay Arı Kolonisi algoritması ile Hanoi su dağıtım şebekesi üzerinde maliyet optimizasyonu yapılmıştır. Mevcut çalışma kapsamında en başarılı algoritmanın belirlenmesi için yakınsama hızı, tutarlılık ve sonuçların dağılımı karşılaştırmalı performans analizi kapsamında incelenmiştir.
Anahtar kelimeler:*Optimizasyon, su dağıtım şebekesi, yapay arı kolonisi, genetik algoritma, parçacık sürü optimizayon algoritması*

Introduction

Collecting, transporting and delivering the necessary water to the customers include different processes. These processes are both crucial for urban life and very expensive. When cost values which were occurred in these processes are investigated, it can be seen that the cost rate of water transmission and distribution systems over total cost is very high. Ozdaglar et al. (2006), asserted that cost rate of water transmission and distribution systems over total project cost is nearly 56%,Dandy & Engelhardt (2006) asserted that pipe cost in the Water Distribution Networks (WDNs) constitute nearly 70% of the total cost. On the other hand, some researchers claim that total project cost can be reduced by approximately 50% with the use of the suitable pipe diameters (Murphy et. al, 1993; Quindry et. al, 1981).

Presence of high-cost values over water transmission and distribution systems canalized the researchers to study in this field. Researchers have been interested in especially WDNs field in time. However, the presence of different design criteria about the WDNs, the multitude of nonlinear equation to determine the pipe diameter and large interval of the commercial pipe sizes made the design become harder.

In this way, it has become an optimization problem with the minimum cost value and at the same time determining the best system, that meets the necessary conditions. Cost optimization has become a necessity both in designing a new system and in the rehabilitation of an existing system.

Initially, traditional optimization algorithms like linear and non-linear programming were used in this field in the literature. Particularly linear programming method has been preferred and accepted by many researchers for a long time (Tospornsampan et. al, 2007). In the 1990s, stochastic optimization algorithms like Tabu Search, Genetic Algorithms (GA) and Simulated Annealing methods were used for determining the optimum system. Recently, Meta-Heuristic optimization algorithms like Particle Swarm Optimization (PSO) and Shuffled Frog Leaping optimization algorithms that modeling the behavior of different creatures, which live in a flock format, were used to determine the optimum system.

In the literature, performance of algorithms was compared with using different algorithms from some benchmark networks like Alperovits and Shamir (Alperovits& Shamir, 1977) network, NewYork WDN (Schaake& Lai, 1969), Hanoi WDN (Fujiwara &Khang, 1990) and Two-Loop network (Kadu et. al, 2008). Minimum cost values, evaluation numbers, convergence velocities and stability of algorithms were compared.

In this study, Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) methods, commonly used in the literature, and recently revealed Artificial Bee Colony (ABC) algorithm method were applied to Hanoi water distribution network for the purpose of cost optimization. To determine the best performing algorithm for this case study; the comparative performance analysis of convergence velocity, stability, and distribution of results was examined.

Main objective of this study is to test the performance of ABC algorithm, which was revealed recently in the literature. In order to compare results of ABC algorithm, GA and PSO algorithms were also used for Hanoi WDN. Algorithms were run under equal conditions as much as possible to control the performance metrics properly in comparative performance analysis.

Material and Methods

Study Area: Hanoi WDN

Hanoi WDN which was first presented by Fujiwara & Khang (1990) became a benchmark network (Figure 1). Numerous researchers (Kadu et. al, 2008; Afshar & Marino, 2005; Babu & Vijayalakshmi, 2013; Cisty, 2010; Cunha & Ribeiro, 2004; Cunha & Sousa, 1999; Geem, 2009; Perelman & Ostfeld, 2007; Vasan & Simonovic, 2010) preferred to study this network in the literature. This network has one source, 31 joints and 34 pipes. All joints in the network have 0m elevations. The minimum pressure value is assumed as 30m. Detailed numeric information about Hanoi WDN can be found in Cunha & Sousa (1999).

Optimum Design of WDNs

There are some criteria for the design of WDNs. These criteria must be satisfied for all nodes and all pipes of a WDN. At first, the diameter of pipes is determined and head loses for all pipes are calculated by using Hazen-Williams formula in Eq. (1).

$$Hk_j = \left[\frac{Q_j}{0.2785 C_{HW} D_j^{2.63}} \right]^{1.852} L_j \quad (1)$$

whereHk_j shows the head loss in pipe j., $Q_j$expresses the flow running through the pipe j., C_{HW} expresses the Hazen-Williams roughness coefficient, which varies depending on the type of the pipe, and D_j expresses the diameter of the respective pipe. Head loss values are calculated by using this formula. A head loss in any pipe is extracted from the previous node's hydraulic head value along the flow directions to determine the P_i pressure values for each joint. Pressure condition in Eq. (2) must be satisfied for each joint.

$$P_{min} \le P_i \le P_{max} \ \forall_i = 1,2,3,........,N \quad (2)$$

Herein P_{min} and P_{max} show the minimum and maximum pressure values in joint i respectively for N nodes. In addition, while the flow coming into a node is shown by Q_i^{in}, the flow going out of a node is shown by Q_i^{out} and if any, the flow drained from a node is shown by Q_i^{demand}, the continuity condition given in Eq. (3) should be met.

$$Q_i^{in} - Q_i^{out} - Q_i^{demand} = 0 \ \forall_i = 1,2,3,........,N \quad (3)$$

In the energy conditions given in Eq. (4), sum of the head losses through m pipes in any flow direction must be equal to the sum of the head losses which occurred in other flow direction through n pipes. γ_{min} parameter in Eq.(4) is defined in related codes.

$$\sum_{i=1}^{m} Hk_i - \sum_{j=1}^{n} Hk_j = \gamma \cong 0 \le \gamma_{min} \quad (4)$$

Eventually objective function that is given in Eq. (5) is run with last pipe sizes. Herein Z shows objective function, D_j the diameter of the pipe no j, $C(D_j)$ the unit cost for diameter D_j and L_j the length of pipe no j. δ parameter in Eq. (5) shows the penalty cost. When a pipe system doesn't satisfy any criteria, a penalty cost value occurs and total cost of the system is increased artificially. In this way, unwanted solutions can be eliminated.

$$Z = \sum_{i=1}^{M} C(D_j) \cdot L_j + \delta \tag{5}$$

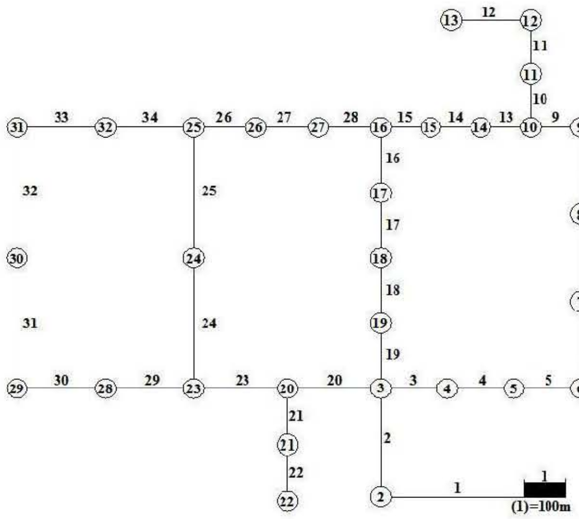

Figure 1. Hanoi WDN (Cunha & Sousa, 1999).

ABC, PSO and GA

Heuristic optimization algorithms model the behavior of different creatures that live in nature and these algorithms search the optimal solution in this way. It cannot be said that these algorithms always find the global optimum solution. But they can find optimal solutions which exist near the best solution. Besides, heuristic optimization algorithms can be identified as an applicable and preferable (Karaboga, 2004).

Artificial Bee Colony (ABC) algorithms were firstly asserted by Karaboga (2005)and behavior of food seeking of bees are modeled in this method. In the ABC method, certain bees leave from the hive and start to search for sources of food places. These bees come back to their hive for informing other bees about the food places. Then, bees search for better food sources near the previous food places. In this way, bees try to find the best food places, which represents the best solution points for any problem. PSO method, which was firstly proposed by Kennedy & Eberhart (1995),was inspired by the food searching behavior of birds and fishes in a flock format. GA method uses evaluations of new generations to reach the best solution points.

ABC, PSO and GA methods start and complete the solution in a similar way like the other optimization algorithms. At first X_{ij} initial solution points are defined with Eq. (6) in the range of x_j^{min} and x_j^{max} limit values.

$$x_{ij}=x_j^{min}+rand(0,1)(x_j^{max}-x_j^{min}) \qquad i = 1 \ldots\ldots PN,\ j = 1 \ldots\ldots\ldots D_p \tag{6}$$

Herein PN means the population number, which is the number of bees for ABC method, number of particles for PSO method and number of chromosomes for GA method. PN can take different values for different problems. D_p parameter expresses the dimension of the problem. For example, D_p can be defined as a pipe number for a WDN problem.

After the definition of x_{ij} solution points, initial solution matrix occurs. Row and column number can be defined as PN and D_p respectively. Every row of the solution matrix describes a different WDN solution. Then, the objective function in Eq. (5) run and total cost values are calculated for each WDN solutions. The best solution that has a minimum total cost value is saved as a global optimum value. After this step, ABC, PSO and GA methods search for better global optimum solutions and better global optimum values with different operators.

ABC algorithm searches for better solutions around previous solutions. In the PSO algorithm; solution points, which were previously found out, are updated to the new best solution points. GA method uses crossover and mutation operators to change genes' location. Best solution points and cost values are saved after each iteration. If an algorithm reaches a better result during optimization, the location of the solution points and cost values are replaced. When determined iteration number is obtained or predefined cost value is reached, the algorithm is stopped.

Results

In order to determine the differences between three methodologies; ABC, PSO and GA methods were run with the same objective function, discharge values and individual numbers (number of bees for ABC method, number of particles for PSO method and number of chromosomes for GA method). Individual numbers were defined as 2, 5, 10 and 20 times of dimension number that was 34 for Hanoi WDN to observe the relations between the individual number and results. Eventually, individual numbers were accepted as 68, 170, 340 and 680. Iteration number was accepted as 1000 for all study. In all methods, 30 trials were carried out to observe the stability. Coefficient of C_{HW} for Hazen-Williams formula was accepted as 130 for all pipes. Diameter values were identified in a continuous manner and the results were discretized by rounding to new (nearest) diameter values.

In PSO method, acceleration parameters were accepted as 2.0 for c_1 and c_2. Inertia weights were accepted as 0.9 for w_{max} and 0.4 for w_{min}. The limit value for acceleration parameters was sustained as 0.20m for PSO study (v_{max}=0.20 m, v_{min}=-0.20 m). In GA method, crossover rate was0.15 and the mutation rate was0.40. Tournament selection was used from the selection operators for GA method.

At the end of the study, statistical parameters about cost values for 30 trials and box plot graph for these results were shown in Table 1 and Figure 2 respectively. In order to show the stability properly, the variation of standard deviation was given in Figure 3.

When the optimization results were observed it was seen that the ABC method reached better results in spite of PSO and GA in terms of all statistical parameters. The ABC method obtained lower minimum, average, maximum cost values as shown in Table 1 and lower standard deviation value as shown in Figure. 3. Furthermore, results of the ABC method have more stable behavior as shown in Figure 2. On the other hand, it was observed that PSO results had a lower performance metrics than ABC and GA methods. PSO method obtained higher minimum, average and maximum cost values as shown in Table 1.

Generally, the relation between the performance of the method and the individual number was not revealed clearly. However, it was seen that the average cost values were decreased with the increasing individual numbers as shown in Table 1. In this context most stable behavior was obtained with the PSO method. PSO method reached better solutions while the individual number increased (Table 1).

Convergence graphs give information about the convergence velocity of the algorithms. In this mean, convergence graphs of the best results for each method are shown in Figure 4 for the individual numbers of 2D, 5D, 10D and 20D. As a summary, it was observed that even though the PSO algorithm reached the optimum cost value earlier than the other methods, it obtained higher cost values than GA and ABC ultimately.

Table 1

Statistical Parameters of Optimum Cost Values for ABC, PSO and GA

Parameters	ABC ($x10^6$)			
	Number of Bees			
	2D (68)	5D (170)	10D (340)	20D (680)
Min.	6.240	6.112	6.120	6.120
Ave.	6.342	6.270	6.245	6.225
Max.	6.507	6.434	6.355	6.330
Std.*	0.058	0.067	0.064	0.056
Parameters	PSO ($x10^6$)			
	Number of Particles			
	2D (68)	5D (170)	10D (340)	20D (680)
Min.	6.926	6.576	6.543	6.417
Ave.	7.386	7.116	6.865	6.749
Max.	7.737	7.493	7.161	7.060
Std.	0.237	0.262	0.184	0.176
Parameters	GA ($x10^6$)			
	Number of Chromosomes			
	2D (68)	5D (170)	10D (340)	20D (680)
Min.	6.380	6.192	6.183	6.250
Ave.	6.829	6.719	6.569	6.522
Max.	7.653	7.874	6.988	6.913
Std.	0.268	0.339	0.187	0.151

Note.Std. = Standard Deviation

Furthermore, it was observed that the PSO algorithm caught the local minimum points. The GA method reached the optimum cost values later than the PSO and ABC methods. On the other hand, a correlation between convergence performance and individual numbers was observed for the GA method. As the individual numbers increased, the GA method gave the optimum value faster.

As a result of this study, the ABC algorithm showed a better performance than PSO and GA for Hanoi WDN. ABC algorithm obtained the lower cost values (Table 1) with a more stable structure (Figure 2 and Figure 3).

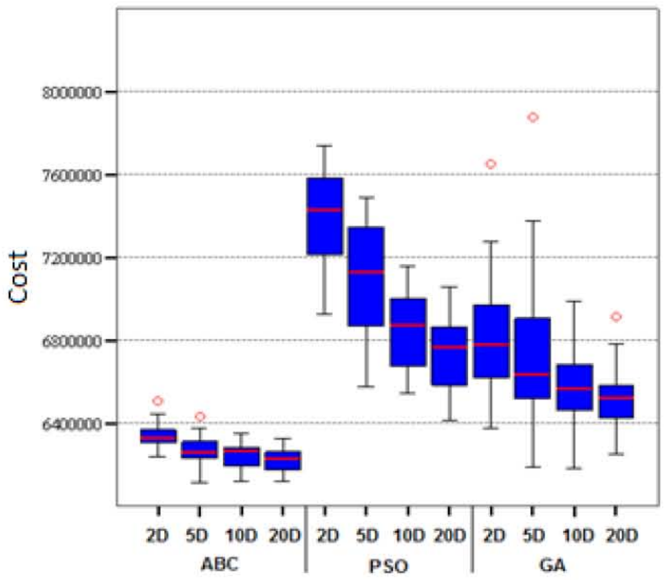

Figure 2. The Box Plot graph of optimization results for Hanoi WDN.

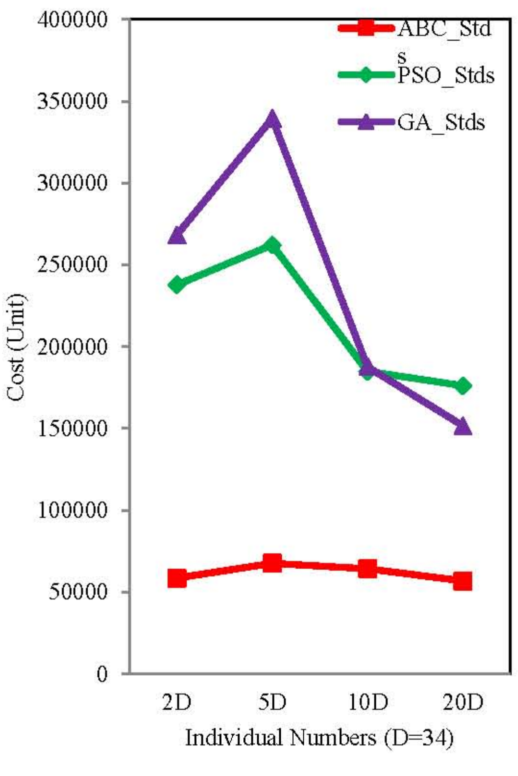

Figure 3. Variation of standard deviation values for Hanoi WDN.

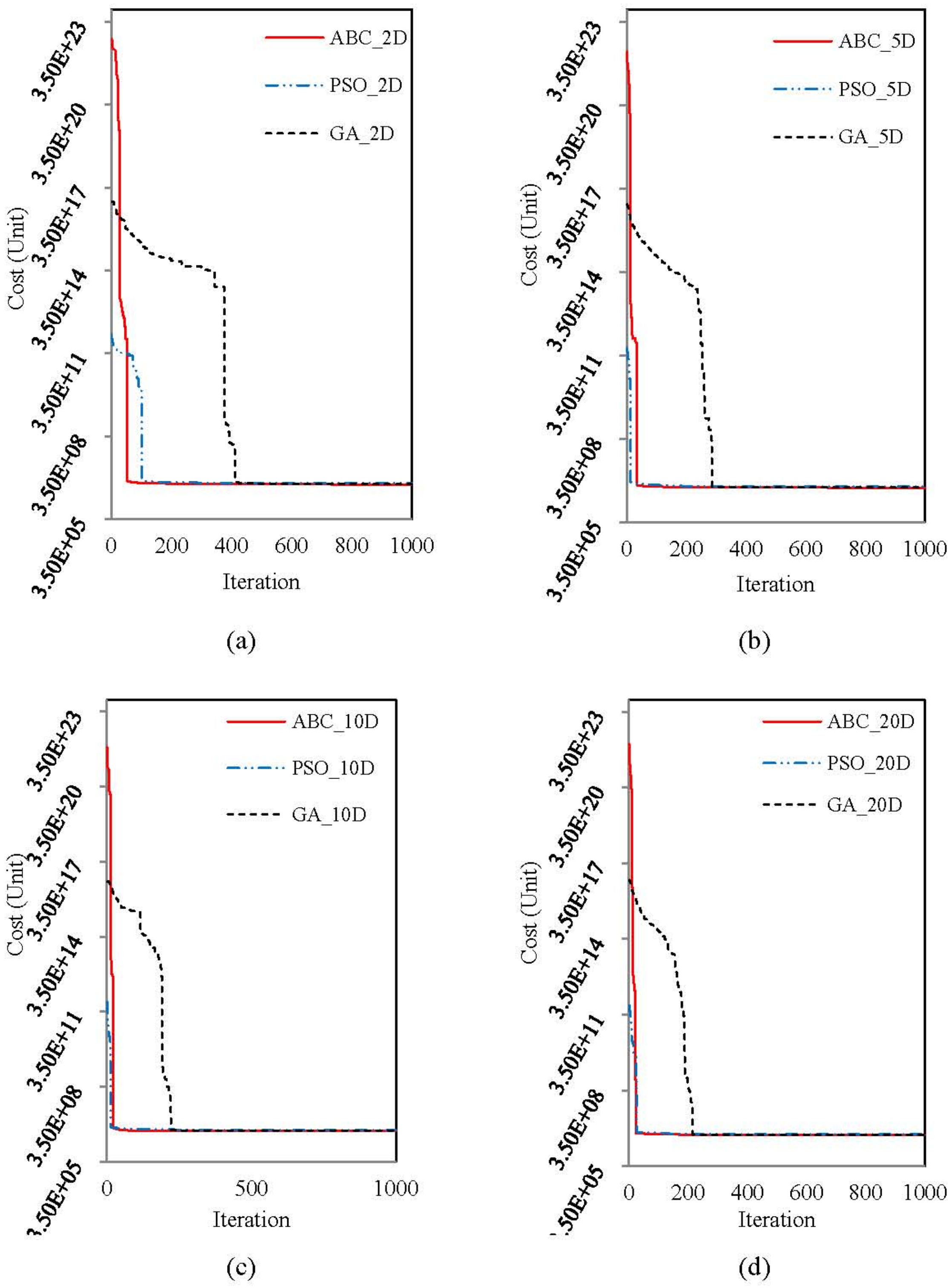

Figure 4. Convergence graphs of each method for the individual numbers of 2D=64 (a), 5D=170 (b), 10D=340 (c) and 20D=680(d).

Discussion and Conclusion

The main purpose of this study is to search the performance of the ABC optimization algorithm for the WDN problem. Therefore, the GA and PSO algorithms were preferred as a reference method for the comparison of each method. All of the three methods ran with the same initial conditions. Three optimization algorithms analyzed by using comparative performance analysis for Hanoi WDN. At the end of the study, it was observed that the ABC algorithm obtained minimum cost values with a more stable behavior than the PSO and GA methods. Furthermore, the ABC method reached the optimum cost value faster than the other two methods' general convergence patterns. Finally, it was revealed that the ABC algorithm performed better than the PSO and GA methods for Hanoi WDN.

Consequently, the optimization process has been a necessity nowadays especially for the WDN problems which are so expensive structures. Since, the structure of the optimization methods are so different that it cannot be claimed a certain optimization method performs well for a certain optimization problem (Yilmaz, 2015). Therefore, different optimization methods should be tried and the results of these methods should be compared with each other. In this way, engineering functions can be serviced with fewer costs.

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Extended Turkish Abstract
(Genişletilmiş Türkçe Özet)

Hanoi Su Dağıtım Şebekesinin Meta-Sezgisel Optimizasyon Algoritmaları ile Maliyet Optimizasyonu

Suyun kaynağından toplanmasıyla başlayıp iletilmesi ve biriktirilmesiyle devam eden ve su dağıtım şebekeleri aracılığıyla son kullanıcıya ulaştırılmasıyla son bulan süreç, bir dizi yüksek maliyetli aşamayı içermektedir. Bu süreçlerin toplam maliyetleri içerisinde su iletim ve dağıtım sistemlerinin oranı oldukça yüksektir. Bu konuda yapılmış olan bazı çalışmalar, su dağıtım şebekelerinin toplam proje maliyeti içerisindeki oranının yaklaşık %70'e kadar çıkabildiğini göstermiştir. Su dağıtım şebekelerinin yüksek maliyet değerleri içermesinin yanısıra hidrolik hesaplamalarındaki lineer olmayan ifadelerin çokluğu, şebeke sistemlerinde istenilen bir takım kısıtlar ve kullanılan ticari boru tip ve çap seçeneklerinin oldukça fazla olması bir şebeke sisteminin istenilen şekilde tasarlanmasını güçleştirmektedir.

Bir su dağıtım şebekesinin hem minimum maliyet değerine hemde istenilen diğer şartlara sahip olarak tasarlanması zaman içerisinde bir optimizasyon problemi haline gelmiştir. Bilgisayar teknolojilerindeki gelişime paralel olarak optimizasyon alanında sürekli yeni yöntemler ortaya atılmıştır. Araştırmacılar ortaya atılan bu optimizasyon tekniklerini kullanarak en uygun şebeke sisteminin belirlenmesi konusunda yaklaşık son 50 yıldır çalışmalar yürütmektedirler.

Bu konuda yapılmış olan çalışmalara ilişkin literatür incelendiğinde:Özellikle bazı Benchmark (Örnek) şebekelerinin tercih edildiği ve araştırmacıların kullandıkları algoritmaları bu Benchmark şebekeler üzerinde deneyerek yöntemlerinin başarılarını test ettikleri görülmektedir. Yaygın olarak kullanılan Bencmark şebekelerinin bazıları Alperovits ve Shamir Şebekesi. Hanoi su dağıtım şebekesi, New York su dağıtım şebekesi ve İki Gözlü şebeke olarak ifade edilebilir.

Mevcut çalışmada Benchmark şebeke olarak Hanoi su dağıtım şebekesi seçilmiştir. Bu şebeke üzerinde literatürde yaygın olarak kullanılan Parçacık Sürü Optimizasyon (PSO) ve Genetik Algoritma (GA) yöntemlerine ilave olarak bu konuda yeni bir yöntem olması bakımından önemli olan Yapay Arı Kolonisi (YAK) optimizasyon algoritması kullanılmıştır. Hanoi su dağıtım şebekesi üzerinde kullanılan bu üç yöntemin sonuca ulaşma hızları, kararlılıkları ve minimum maliyet değeri üretebilmedeki başarıları karşılaştırmalı olarak incelenerek mevcut şebeke üzerinde yöntemlerin karşılaştırmalı performans analizi gerçekleştirilmiştir.

Mevcut çalışmada yöntemler arasındaki değerlendirmenin objektif olarak yapılabilmesi amacıyla PSO, GA ve YAK olmak üzere her üç optimizasyon algoritmasıda aynı amaç fonksiyonu ile çalıştırılmış ve her üç yöntem içinde borulardan geçen debi miktarı gibi hidrolik değişkenler aynı olacak şekilde optimizasyon modeli kurulmuştur. Hanoi su dağıtım şebekesi 34 adet borudan oluştuğu için problem 34 boyutlu olarak tasarlanmıştır. Optimizasyon algoritmalarının başarısında önemli bir değişken olan birey sayısı yani YAK için arı sayısı, PSO için parçacık sayısı ve GA için kromozom sayısı, yöntemin başarısının birey sayısı ile değişip değişmediğinin gözlemlenebilmesi amacıyla problemin boyut sayısı olan 34' ün 2, 5, 10 ve 20 katı olacak şekilde 68, 170, 340 ve 680 olarak belirlenmiştir. Yapılan bütün çalışmalarda iterasyon sayısı 1000 olarak kabul edilmiştir. Algoritmaların kararlılıklarının belirlenebilmesi amacıyla her yöntem 30 kere çalıştırılmış ve elde edilen sonuçlara göre yöntemlerin performansları karşılaştırılmıştır.

Yapılan çalışmadan elde edilen sonuçlar incelendiğinde bütün istatistiki parametrelere göre YAK yönteminin PSO ve GA yöntemlerine kıyasla daha başarılı sonuçlar ürettiği görülmektedir. YAK yöntemi diğer iki yönteme göre daha düşük maliyet değerleri üretmiş ve bunun yanında daha düşük standart sapma değeri elde ederek diğer iki yönteme kıyasla daha kararlı bir yapı sergilemiştir.

Genel olarak yöntemlerin başarısı ile birey sayısı arasında net olarak bir ilişki tespit edilememiş olsa da yöntemlerin üretmiş olduğu ortalama maliyet değerlerinin birey sayısı arttıkça azalmış olduğu görülmüştür. Bu kapsamda en belirgin davranış PSO yönteminden elde edilen sonuçlarda görülmektedir. PSO yöntemi birey sayısı arttıkça daha başarılı sonuçlar üretebilmiştir.

Yapılan çalışmalarda iterasyonlar boyunca maliyet değerlerinin değişimini gösteren yakınsama grafikleri yöntemlerin optimum maliyet değerine ulaşma hızlarını değerlendirme bakımından önemlidir. Yakınsama grafikleri incelendiğinde PSO yönteminin optimum maliyet değerine diğer iki yönteme kıyasla daha erken ulaştığı fakat diğer iki yönteme kıyasla daha yüksek maliyet değerlerinin elde edildiği görülmektedir.Bu sonuç PSO yönteminin yerel minimum noktalarına takılma konusunda diğer yöntemlere kıyasla daha hassas ve daha başarısız olduğunu düşündürmüştür. Bunun yanısıra GA yönteminin optimum maliyet değerine YAK ve PSO yöntemlerine kıyasla daha geç ulaştığıda yine yakınsama grafiklerinde görülebilmektedir.

Sonuç olarak bir Benchmark şebeke olan Hanoi su dağıtım şebekesi üzerinde YAK, PSO ve GA olmak üzere 3 adet Meta-Sezgisel optimizasyon algoritması ile yapılmış olan karşılaştırmalı performans analizinde YAK yönteminin diğer iki yönteme kıyasla daha düşük maliyet değerleri elde ettiği, daha düşük standart sapma değeri üreterek daha kararlı bir davranış sergilediği ve optimum maliyet değerine daha erken yakınsadığı sonuçlarına ulaşılmış ve özet olarak YAK yönteminin diğer iki yönteme kıyasla daha yüksek bir performans sergilediği görülmüştür.

Genel olarak optimizasyon algoritmalarının doğası gereği, belirli bir yöntemin her problemde üstün davranış sergileyeceğini iddia etmek doğru değildir. Herhangi bir yöntem bir problem üzerinde başarılı olurken başka bir problem üzerinde başarısız olabillir. Bu yüzden su dağıtım şebekeleri gibi optimizasyonun gerekli olduğu bir alanda belirli bir sistem tasarlanırken mutlaka farklı yöntemler denenmeli ve sonuçlar incelenerek istenilen sistem bu şekilde tasarlanmalıdır. Bu yolla kullanıcılara mühendislik hizmetinin daha kaliteli ve daha düşük maliyetlerle sunulması sağlanabilir.