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Research Article

Application of Bat Algorithm for Transport Network Design Problem

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The requirement of the road services and transportation network development planning came into existence with the development of civilization. In the modern urban transport scenario with the forever mounting amount of vehicles, it is very much essential to tackle network congestion and to minimize the travel time. This work is based on determining the optimal wait time at traffic signals for the microscopic discrete model. The problem is formulated as a bilevel model. The upper layer optimizes the travel time by reducing the wait time at traffic signal and the lower layer solves the stochastic user equilibrium. Soft computing techniques like Genetic Algorithms, Ant Colony Optimization, and many other biologically inspired techniques prove to give good results for bilevel problems. Here this work uses Bat Intelligence to solve the transport network design problem. The results are compared with the existing techniques.

1. Introduction

Nowadays the ever more increasing number of vehicles creates a challenge in the modern urban transportation scenario. For a road network with n number of junctions, there are 2^n possible networks. Thus, finding an optimal path is an important criterion for traffic optimization problem. But in many cases there is a limitation or unavailability of road junction or it is also possible that at a particular instance of time a particular link which seems shorter is unavailable or highly contested. Another profitable way to put up with it can be optimizing the wait time at traffic signals. This will not only save the priceless time of vehicle users, but also reduce congestion, improve road safety, and smooth the progress of medical emergencies and industrial needs.

The need for the transport and road network planning came on track with the expansion of civilization. Abdullaal [1] formulated a solution to vehicular equilibrium network design problem by means of the Hooke-Jeeves' technique with continuous variables. In the year 1985 Yosef Shefi [2] illustrated a flow pattern all the way through an urban network as an upshot of two competing systems. The user of the system, say drivers, passengers, or pedestrians, struggles to travel in a way that breaks down the incompatibility coupled with the transportation system. Also, this incompatibility associated with the travel time is inconsistent and depends somewhat on the usage of the transportation system.

Allsop [3] designed mutually consistent (MC) traffic signal settings and traffic assignment for a medium size road network. Heydecker [4] recommended a linear constraint approximation model and solved the bilevel problem as a constraint optimization problem.

It is not comprehensible a priori which path through the network has the shortest travel time. We can conclude that the responses of the vehicle user can be predicted not dictated. Biologically inspired techniques have proven to give good results in such scenarios. The nature provides a wide range of inspiration in many unusual forms, sizes, and attributes.

Ceylan and Bell [5] integrated GA, traffic assignment (evaluation using TRANSYT), and traffic control (with minimization solved using the Path Flow Estimator (PFE)), and GATRANSPFE was developed to solve network design problem and its performance was put side by side with mutually consistent (MC) solution using numerical examples. The

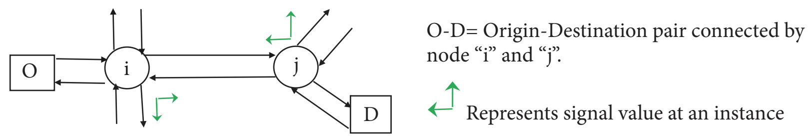


FIGURE 1: An intersection of the network showing an O-D pair connected by a 3-way and a 4-way junction. The green arrows denote the signal values.

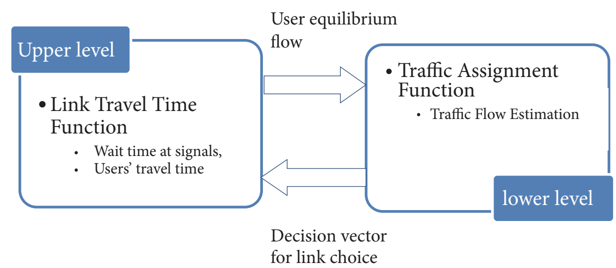


FIGURE 2: Bilevel model for traffic network determination problem.

performance index (PI) was improved by 34% over the MC solution of the problem in 75th generation. Koh [6] used differential evaluation for bilevel continuous network design problem. Ozgur Basken and Sonar Haldenbilen [7] developed an ACO Reduced Search Space (ACORSS) to find better signal timing in the signal setting problem of a bilevel model for traffic optimization problem. Hu Hui [8] solved urban transportation equilibrium network design problem using bilevel programming, and it was solved using PSO and Frank Wolfe. The algorithm was found effective and took less iteration to give a better solution in comparison to Simulated Annealing. S. Srivastava and S. K. Sahana [9, 10] designed a Discrete Evolutionary Model to reduce the waiting time of vehicles at traffic signals within the urban transportation system using level Stackelberg game model 5 test networks with 12, 16, 20, 24, 28 nodes designed using Petri Net. The proposed hybrid technique was solved for optimizing wait time at traffic signals and for SUE. Hybrid algorithm outperformed ACO and GA. Canteralla et al. [11, 12] and many others have previously proposed a discrete model, but most of them were macroscopic simulation models. The proposed model works on the level of sections within a road network and hence can take care of various microscopic tribulations.

Xin-She Yang [13–15] proposed a metaheuristic method, the bat algorithm (BA), inspired by echolocation behavior of bats for continuous constrained optimization problems. BA was found to be more powerful than Particle Swarm Optimization, Genetic Algorithms, and Harmony Search due to its robust parameter control features and frequency tuning abilities. BA proves to give good results for many optimization problems. Kiełkowicz and Damian Grela [16] used BA for nonlinear optimization problems. Abatari et al. [17] proposed a BA inspired method to solve the Optimal Power Flow (OPF) problem. Yassine Saji et al. [18] used BA to solve discrete traveling salesperson problem.

This paper is organized into 5 sections. The first section introduces the paper and discusses some related work. Section 2 gives problem formulation. Section 3 discusses the bat algorithm. Section 4 presents the research methodology and, last, Section 5 discusses 3 test cases and their solution using BA.

2. Problem Formulation

The road network can be taken as a directed graph G= (N, a), where 'N' is the set of nodes; i.e., the road junctions 'a' is the links connecting the junctions as shown in Figure 1. For each pair of origin and destination (O-D) there is a nonnegative travel demand, d_{rs}. The road network can be taken as a strongly connected graph, where each node "i" is reachable by another node "j" by following the directed path of the network N.

We assume that the links connecting nodes have a travel time function t_a, for assigned rate of flow x_a. The objective is to choose a proper link of set to travel from origin to destination and also to reduce the traffic delay at each junction. The continuous network design model is chosen with budget constraints for the link capacity expansion. Both the objectives are interdependent and can be formulated as a bilevel problem. The upper level is responsible for reducing the travel time of the assigned traveler. The lower level is the traffic assignment model which estimates the traveler flow. The model is shown in Figure 2.

This model can be formulated mathematically as shown below for both the layers.

Upper Level Function

$$\min \mathrm{T}(\mathrm{y}) = \sum_{a\in A}\sum_{a\in A(y)} x_a t_a(x_a) + \mathrm{d}_\mathrm{a}\mathrm{y}_\mathrm{a}$$
$$\text{Such that, } \sum c_a y_a \leq B \tag{1}$$

where A is the set of all links a in the network N. x(y) gives the user equilibrium flow, which is estimated from lower level of the model for the assigned value of link capacity y.

c_a is construction cost for link a and B is the budget.

Table 1: A comparative analysis of best, average, and worst solution for all the 5 networks.

	12 Nodes	16 Nodes	20 Nodes	24 Nodes	28 Nodes
ACO_{best}	62.25	256.82	443.10	480.03	596.50
GA_{best}	70.15	222.25	338.03	459.54	541.21
$ACO\text{-}GA_{best}$	75.40	218.29	332.10	421.29	542.15
BA_{best}	64.81	212.21	320.21	430.31	538.10
ACO_{worst}	90.14	265.02	443.00	480.27	569.17
GA_{worst}	110.21	259.17	450.41	485.17	560.11
$ACO\text{-}GA_{worst}$	85.01	242.33	421.36	479.33	542.65
BA_{worst}	122.02	273.36	465.22	511.25	588.17
ACO_{avg}	92.14	215.65	425.39	465.14	560.34
GA_{avg}	103.21	245.24	425.37	438.54	540.74
$ACO\text{-}GA_{avg}$	87.27	220.14	414.26	450.94	528.28
BA_{avg}	93.12	242.94	399.58	465.79	561.16

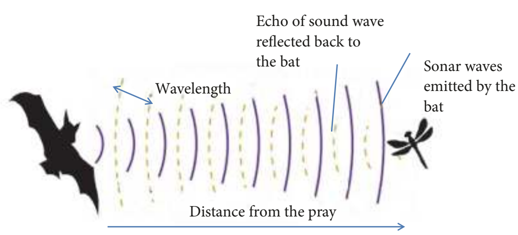


Figure 3: Echolocation behavior of the microbats.

Lower Level Function

$$\min \sum_{a\in A} \int_0^{x_a} t_a(u)\,du$$
$$\text{Such that, } \sum f_k = d_{ij} \quad f_k \geq 0 \qquad (2)$$
$$\sum_{rs}\sum f_k \delta_{ij} = \mathrm{x_a} \quad \forall \delta_{ij} = \begin{cases} 1; & if\ a\ \in k \\ 0; & \end{cases}$$

where f is the flow on path k and r-s are the nodes on the path connecting O-D pair.

3. Bat Algorithm

Bat algorithm is an innovative technique proving to give better solution than many popular traditional and heuristic algorithms [9, 10] for solving complex engineering problems. Bat algorithm is based on the echolocation of microbats. Echolocation (echolocation) is a fascinating sonar wave emitted by the microbats; it helps them find prey and, in some magical ways, they are able to discriminate the different kinds of obstacles or danger on the way towards the prey in complete darkness. An illustration is shown in Figure 3.

The bats emit loud ultrasonic sound waves and listen to the echo that reflects back from the surrounding objects. The bat algorithm uses some idolized rules for simplicity.

(1) Bats use echolocation to sense prey, predator, or any barriers in the path and distance.

(2) Bats fly with a velocity v_i and position x_i. They have frequency f and loudness a_i to reach their prey. They can adjust the frequency of pulse emission r.

(3) As they get close to the prey, pulse increases and loudness decreases.

Figure 4 presents a flow diagram of bat algorithm.

4. Research Methodology

The projected method for solving the TNDP is based on bilevel model. Figure 5 presents a generalized solution technique used for the problem. The upper layer objective function is solved using bat algorithm and the obtained solution is further used to optimize the lower layer.

The frequency of bats $[Q_{min}, Q_{max}] = [0, n]$ where n is the number of nodes in the network. Pulse rate and loudness r_i and a_i vary within the range [0, 1].

5. Results and Discussion

This paper considers 3 sets of test cases. 1st one is taken from [9, 10]. In this paper 5 networks are taken. The budget constraints are not considered in this test case. 2nd test case works on a 16-link problem adapted from [20]. The 3rd test case is based on Sioux Falls problem adapted from [20, 21].

5.1. Test Case 1. Five test cases were adapted from [9, 10] corresponding to five different networks with following specifications: 12-node network, 4 intersections; 16-node network, 6 intersections; 20-node network, 8 intersections; 24-node network, 10 intersections; 28-node network, 12 intersections. Figure 6 shows a 12-node network showing signal values. Figure 7 shows 16-, 20-, 24-, and 28-node networks.

The termination condition for BA is taken as 100 iterations. This termination condition was set up by experiment on several run time results. Intersections were implemented using Origin-Destination nodes with extra features like wait time at signal, signal values, travel time on the link, positional information on the links attached, and other delays.

There were certain assumptions made to simplify the implementation, maintaining the integrity of the problem. Every Origin-Destination pair in the chosen networks is connected through at least one intersection. Lower layer statistics were generated randomly to simulate its function as an input to the upper layer. Table 1 shows the results obtained for the objective function value (OFV) in test case 1.

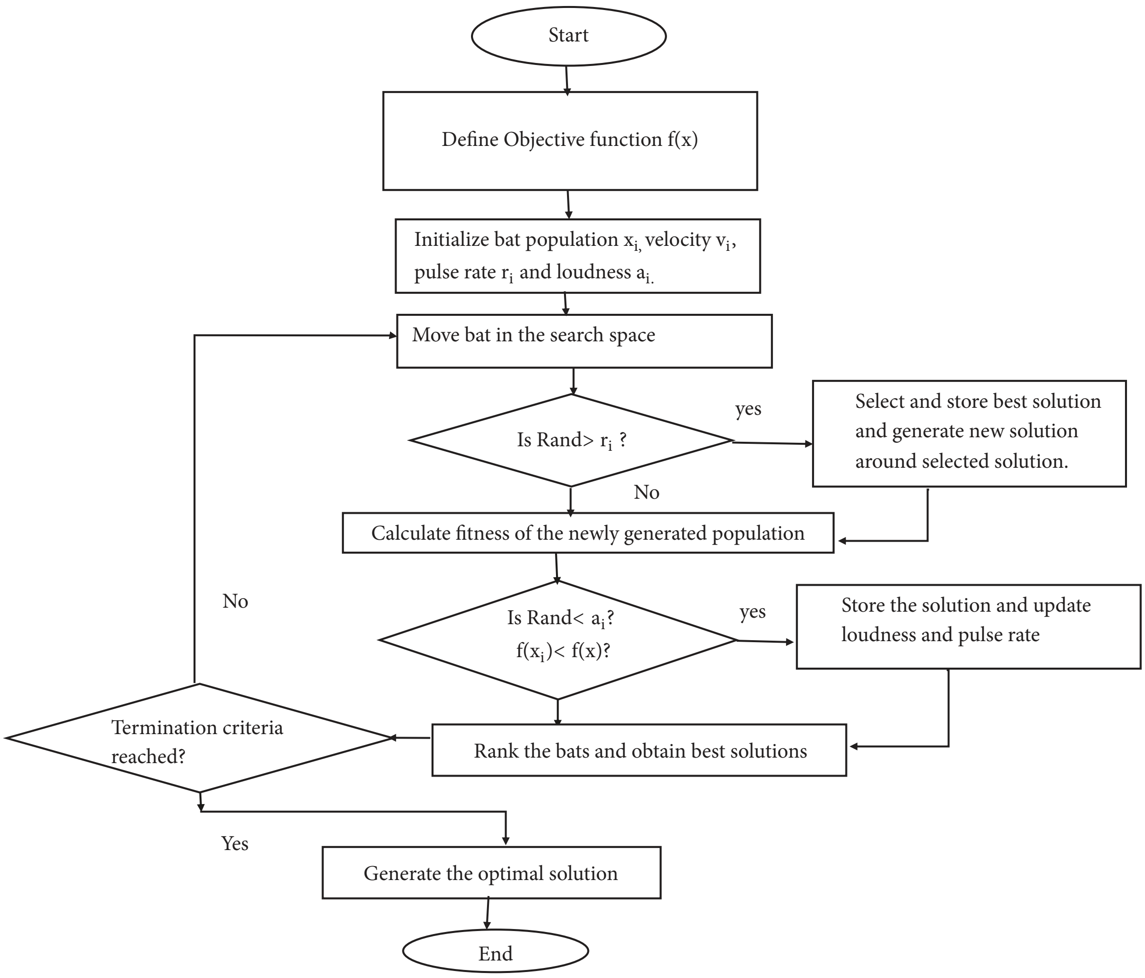


Figure 4: Bat algorithm.

The results for BA are weighed against ACO, GA, and hybrid ACO-GA [9, 10]. Figure 8 shows the best solution for the algorithms. BA establishes the best results compared to the other three for 12, 16, and 20 nodes, but for 24 nodes and 28 nodes ACO and Hybrid algorithm outperform BA.

Figure 9 presents the worst performance of all the four algorithms. It was observed that the hybrid algorithm performs the best among the algorithms. In most of the cases BA gives the worst solution in comparison to the other 3 algorithms.

Figure 10 presents the average solution for ACO, GA, hybrid ACO-GA, and BA. It was observed that the hybrid ACO-GA outperforms ACO, GA, and BA. The average wait time for BA is found to be higher than the other techniques despite the fact that it gave the best solutions in comparison to the rest of the techniques in many cases.

The ranges of all the four algorithms, ACO, GA, hybrid ACO-GA, and BA, are put side by side in Figure 11. It can be observed that BA explores the highest range of solution sets.

Table 2: Travel demand scenario.

	Demand from node 1 to 6	Demand from node 6 to 1	Total demand
Case 1	5	10	15
Case 2	10	20	30

5.2. Test Case 2: 16-Link Network. Several researchers have tested the performance of continuous network design problem on multiple networks. A widely used 16-link network with 6 nodes is adapted from Suwansirikul et al. [20]. The test network is shown in Figure 12.

The continuous network design problem is executed for 3 test cases with different demand scenarios for the given network. The travel demands are shown in Table 2.

The 16-link network problem is estimated using several techniques like traditional H-J, EDO, SA, and CS by different researchers as mentioned in Table 3. A comparative analysis of BA in both demand scenarios is given in Tables 4 and 5.

Table 3: Techniques and references of the test case 2.

Technique	Acronym	References
Modular In-core Nonlinear Optimization System	MINOS	Suwansirikul et al. [19]
Hooke-Jeeves algorithm	H-J	Abdulaal and LeBlanc [1]
Equilibrium Decomposed Optimization	EDO	Suwansirikul et al. [19]
Simulated Annealing algorithm	SA	Friesz et al. [20]
Cuckoo Search Algorithm with Lévy Flights	CS	Ozgur Baskan [21]
Particle Swarm Optimization	PSO	Hu Hui [8]
Bat Algorithm	BA	This paper

Table 4: Solution of demand scenario 1 for TNDP.

	MINOS	H-J	EDO	SA	CS	BA
y1						
y2						
y3	**00**	**1.2**	**0.13**			
y4						
y5						
y6	**6.58**	**3.00**	**6.26**	**3.16**	**5.1894**	**3.18**
y7						
y8						
y9						
y10						
y11						
y12						
y13						
y14						
y15	**7.01**	**3.00**	**0.13**			**5.45**
y16	**0.22**	**2.80**	**6.26**	**6.724**	**7.6016**	**7.21**
OFV	**211.25**	**215.08**	**201.84**	**198.10**	**199.32**	**199.21**
No. of UE Assignment		**54**	**10**	**18300**	**3**	**72**

Table 5: Solution of demand scenario 2 for TNDP.

	MINOS	H-J	EDO	SA	PSO	CS	BA
y1							
y2	**4.16**	**5.40**	**4.88**		**4.61**	**4.61**	**0.25**
y3	**9.86**	**8.18**	**8.59**	**10.174**	**9.89**	**9.94**	**8.89**
y4							
y5							
y6	**7.17**	**8.1**	**7.48**	**5.77**	**7.3**	**7.38**	**8.66**
y7			**.26**				**0.24**
y8	**0.59**	**0.9**	**.85**		**0.59**		
y9							
y10							
y11							
y12							
y13							
y14	**1.32**	**3.14**	**1.54**			**1.3152**	**0.86**
y15	**19.34**	**8.1**	**0.26**				**14.58**
y16	**.85**	**0.85**	**12.58**	**17.2786**	**20**	**20**	**16.08**
OFV	**557.14**	**557.22**	**540.74**	**528.497**	**523.38**	**522.39**	**521.68**
No. of UE Assignment		**134**	**12**	**24300**	**1160**	**4**	**130**

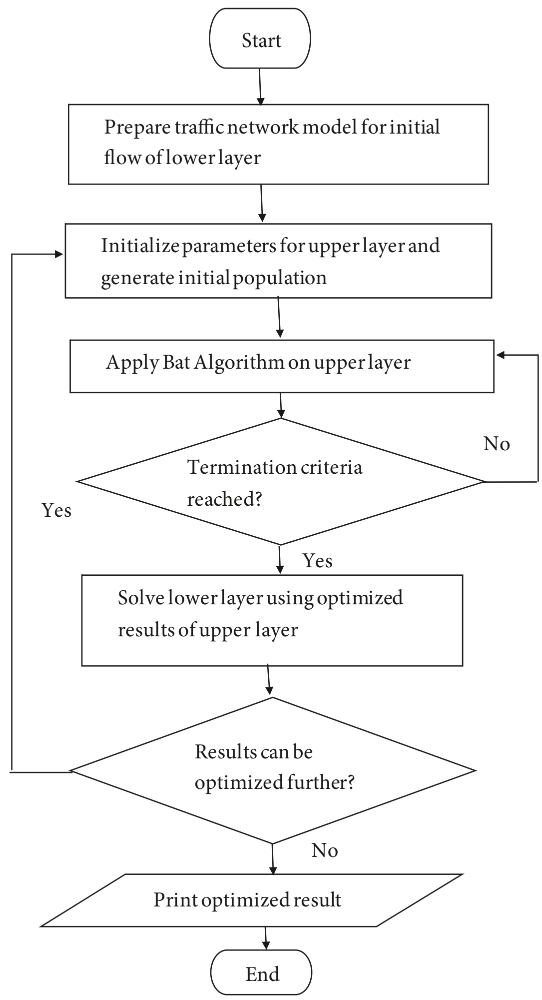


Figure 5: Flowchart for the traffic signal optimization problem using bat algorithm.

Table 6: Techniques and references of test case 3.

Technique	Acronym	References
Hooke-Jeeves algorithm	H-J	Abdulaal and LeBlanc [1]
Simulated Annealing algorithm	SA	Friesz et al. [20]
Gradient Projection method	GP	Chiou [22]
Genetic Algorithm	GA	Mathew and Sarma [23]
Cuckoo Search Algorithm with Lévy Flights	CS	Ozgur Baskan [21]
Harmony Search	HS	Ozgur Baskan[24]
Artificial Bee Colony	ABC	Ozgur Baskan[24]
Differential Evolution	DE	Ozgur Baskan[24]
Bat Algorithm	BA	This paper

5.3. Test Case 3: Sioux Falls Network. A more realistic data for road network is adapted from the city Sioux Falls, South Dakota, situated in the USA. The network is much more complex and appealing to the researchers working on the transport network problem [20–24]. It consists of 24 nodes and 76 links connecting them. Figure 13 shows the adapted network from [20]. The test data are adapted from [20]. Table 6 shows the techniques adapted for comparative analysis of BA and their corresponding references.

The results for Sioux Falls network is shown in Table 7. Figure 14 shows convergence of BA for Sioux Falls network.

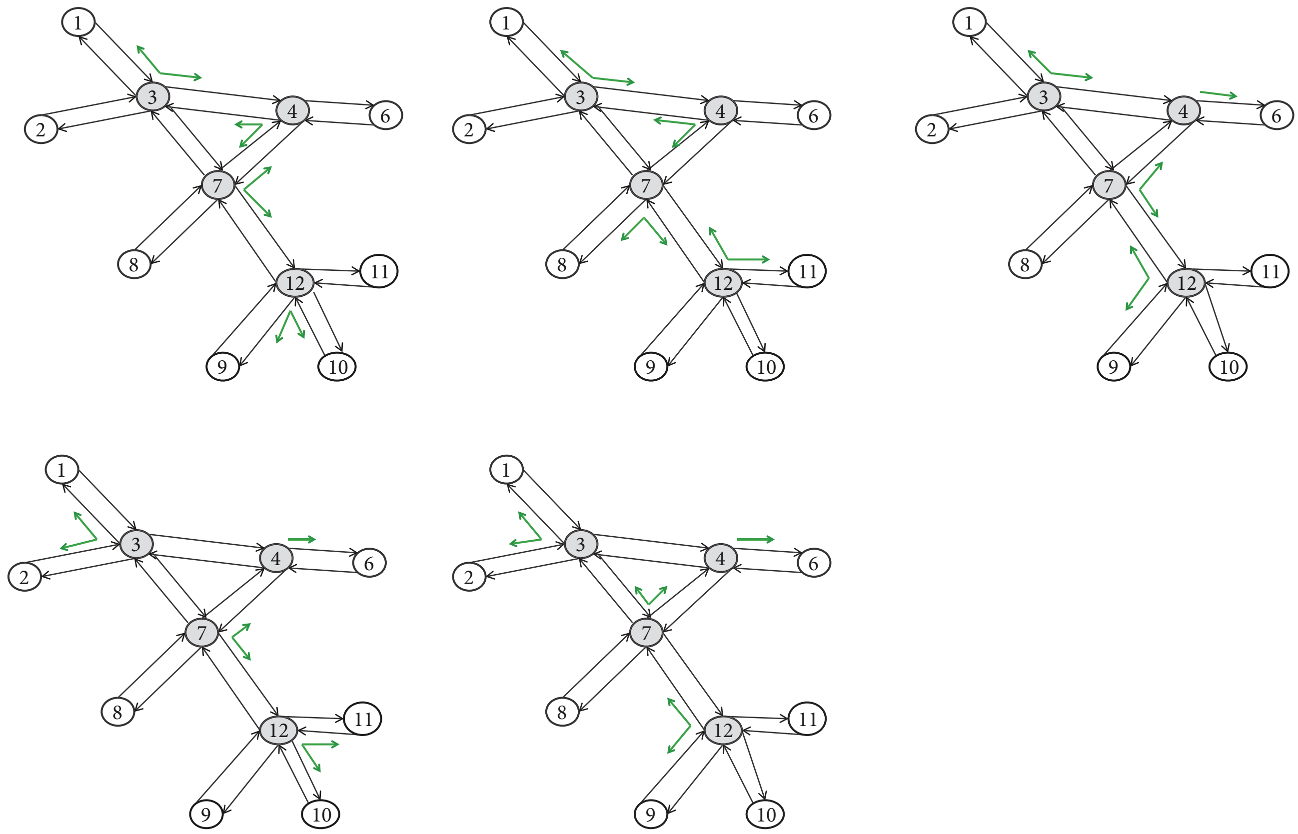


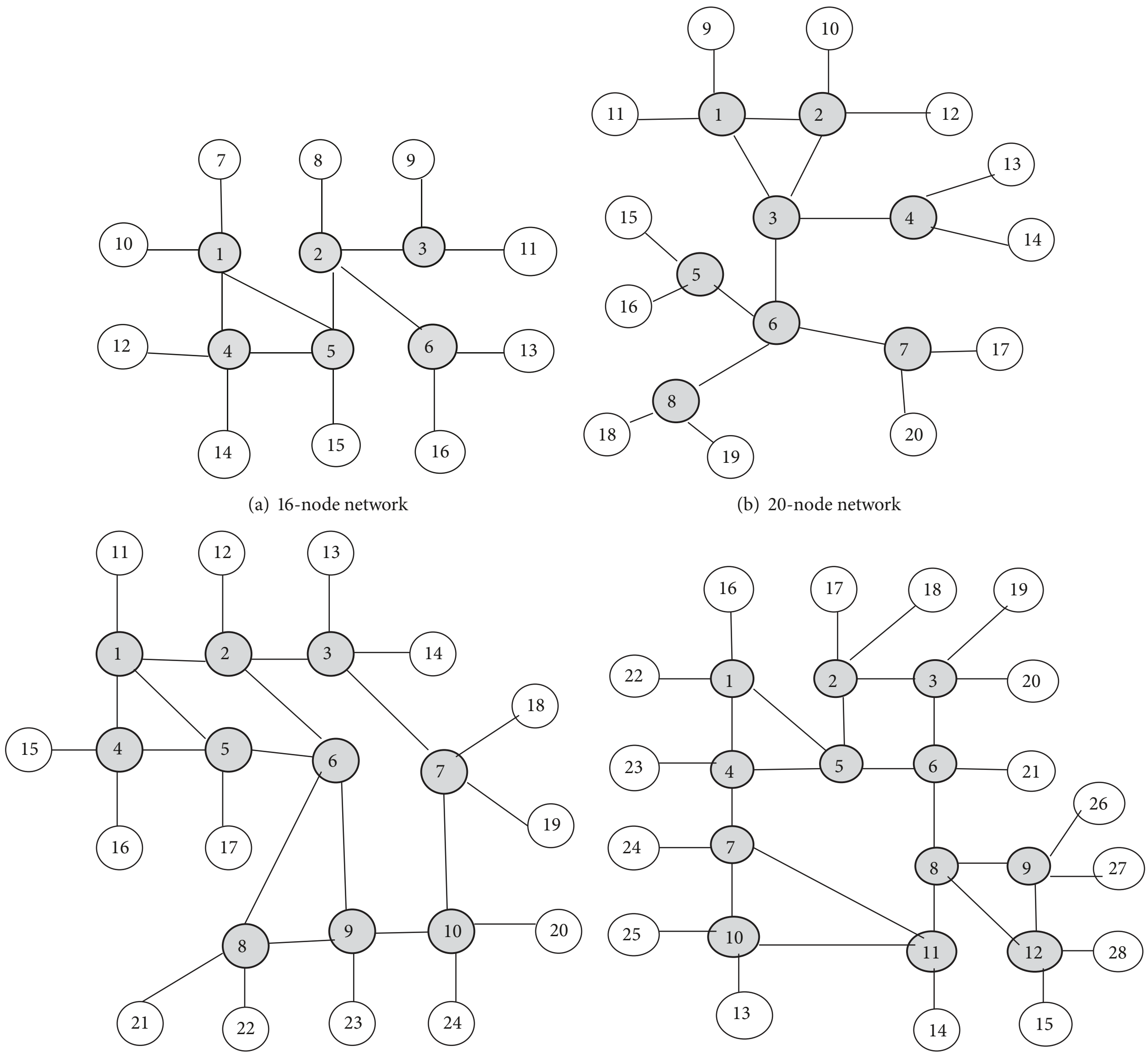
Figure 6: A 12-node test network with 4 intersections showing the signal value of 5 different phases.

Table 7: Comparative analysis of TNDP for Sioux Falls network.

	H-J	SA	GP	GA	CS	HS	ABC	DE	BA
y16	3.8	5.38	4.86	5.17	5.09	4.44	5.91	5.15	4.18
y17	3.6	2.26	4.89	2.94	1.35	1.29	1.95	1.65	2.14
y19	3.8	5.45	1.86	4.72	6.45	5.46	4.86	5.89	3.85
y20	2.4	2.33	1.52	1.76	2.29	2.30	1.75	1.29	2.33
y25	2.8	1.27	2.71	2.39	2.90	0.64	2.54	2.58	0.84
y26	1.4	2.33	2.71	2.91	2.05	2.71	2.98	1.69	0.84
y29	3.2	0.41	6.245	2.92	3.67	4.15	3.69	3.32	3.58
y39	4.0	4.59	5.03	5.99	5.22	3.67	3.77	5.11	3.00
y48	4.0	2.71	3.75	3.63	3.42	4.90	3.02	3.26	3.01
y74	4.0	2.71	3.5	4.43	4.87	4.38	4.91	4.50	4.76
OFV_{BEST}	81.77	80.87	82.71	81.74	81.51	81.83	81.78	81.60	81.31
OFV_{AVG}						81.97	82.02	81.76	82.98
OFV_{WORST}						84.67			85.19
No. of UE Assignment	108	3900	9	77	36	27	32	23	140

6. Conclusion

The simulation work was carried out for various sizes of multiple networks for variant test cases and a number of times. As per the results of test case 1, it can be concluded that BA explores a wide range of solution set and gives better results than GA, ACO, and hybrid ACO-GA. Although the hybrid ACO-GA outperforms ACO, GA, and BA for average solution. BA was compared on a 16-link problem in test case 2. In the 1^{st} demand scenario BA outperformed MINOS, H-J, and CS. Though SA gave a better result than BA, the number of UE assignments solved was multifold higher than BA. In the 2^{nd} demand scenario BA outperformed all the compared techniques, though CS gave a near result in less number of UE assignments.



(a) 16-node network (b) 20-node network (c) 24-node network (d) 28-node network

Figure 7: 16-, 20-, 24-, and 28-node test network.

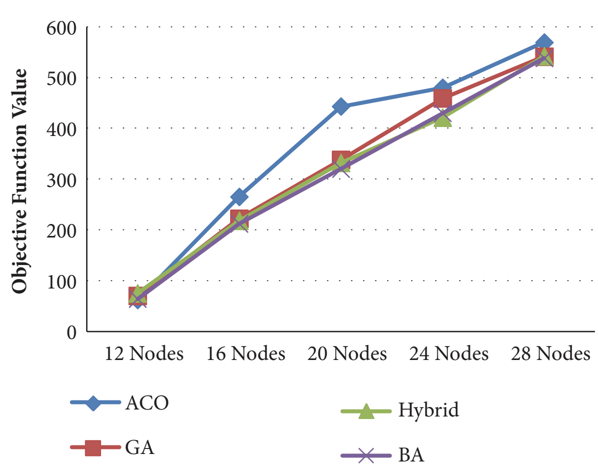


Figure 8: Best solution.

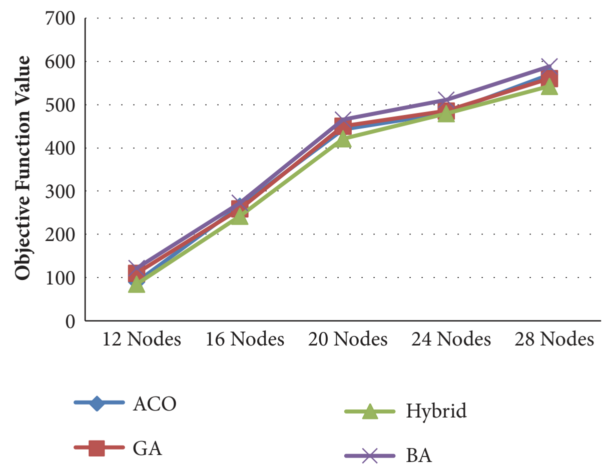


Figure 9: Worst solution.

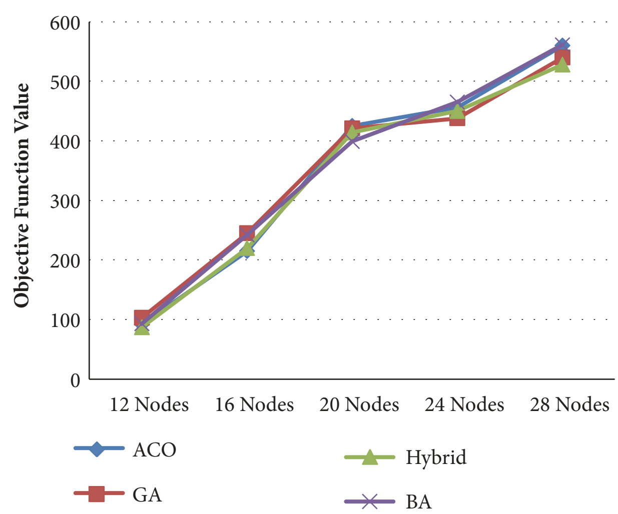


Figure 10: Average solution.

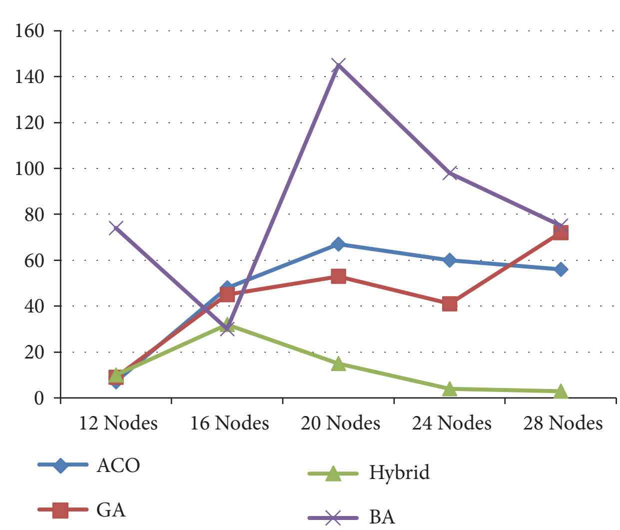


Figure 11: Range of solutions of ACO, GA, hybrid ACO-GA, and BA.

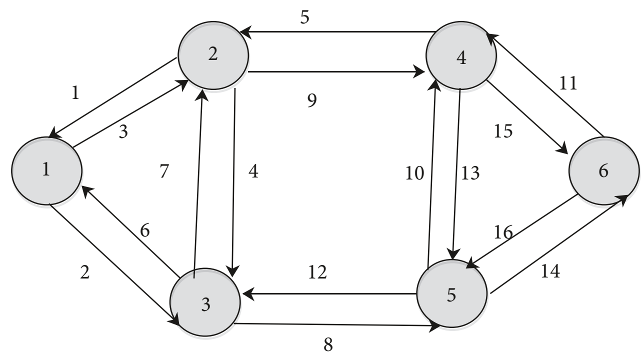


Figure 12: 16-link, 6-node network.

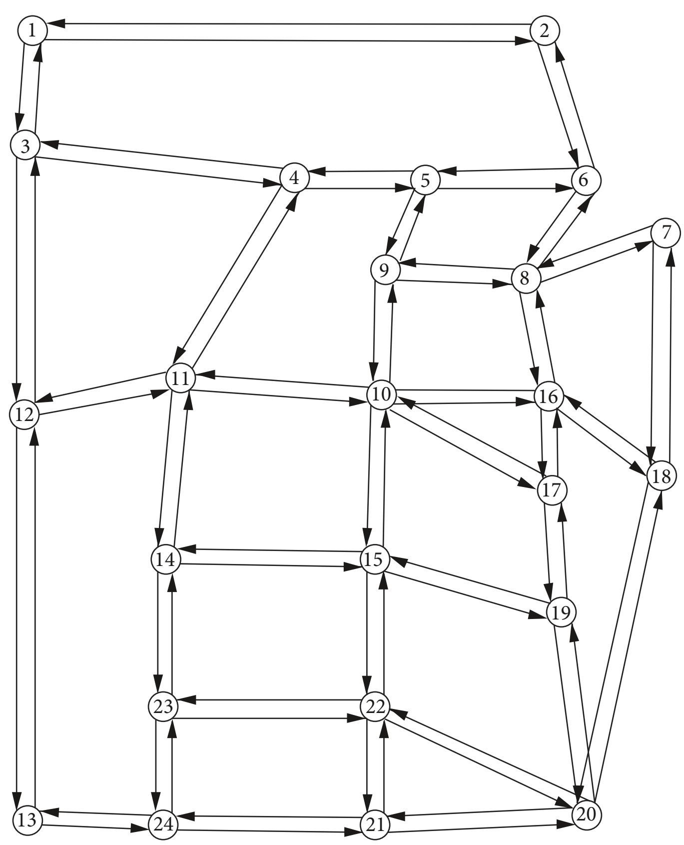


Figure 13: Sioux Falls network.

In the third test case, BA is compared with H-J, SA, GP, GA, CS, HS, ABC, and DE. For the best solution of the objective function value, BA outperforms all the mentioned techniques. For the average value among HS, ABC, and DE, BA gives the higher objective function value. The range of solution for BA seems to be on the higher side. A value of worst solution for HS is given which is better than the worst solution of BA. In future more improvements can be carried out on the proposed algorithm and can be implemented to give a much better solution

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

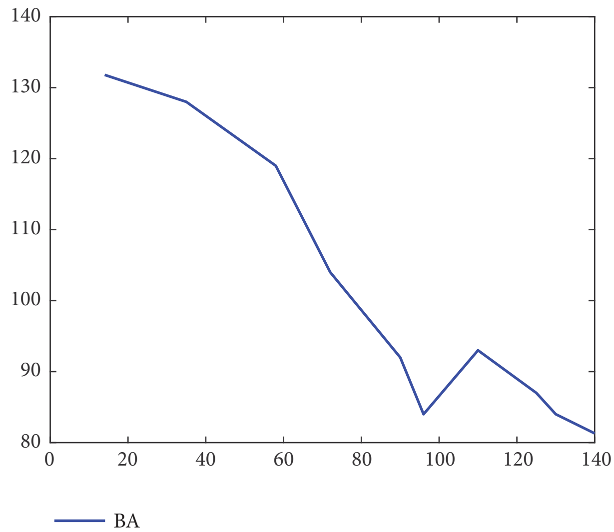


Figure 14: Convergence of BA.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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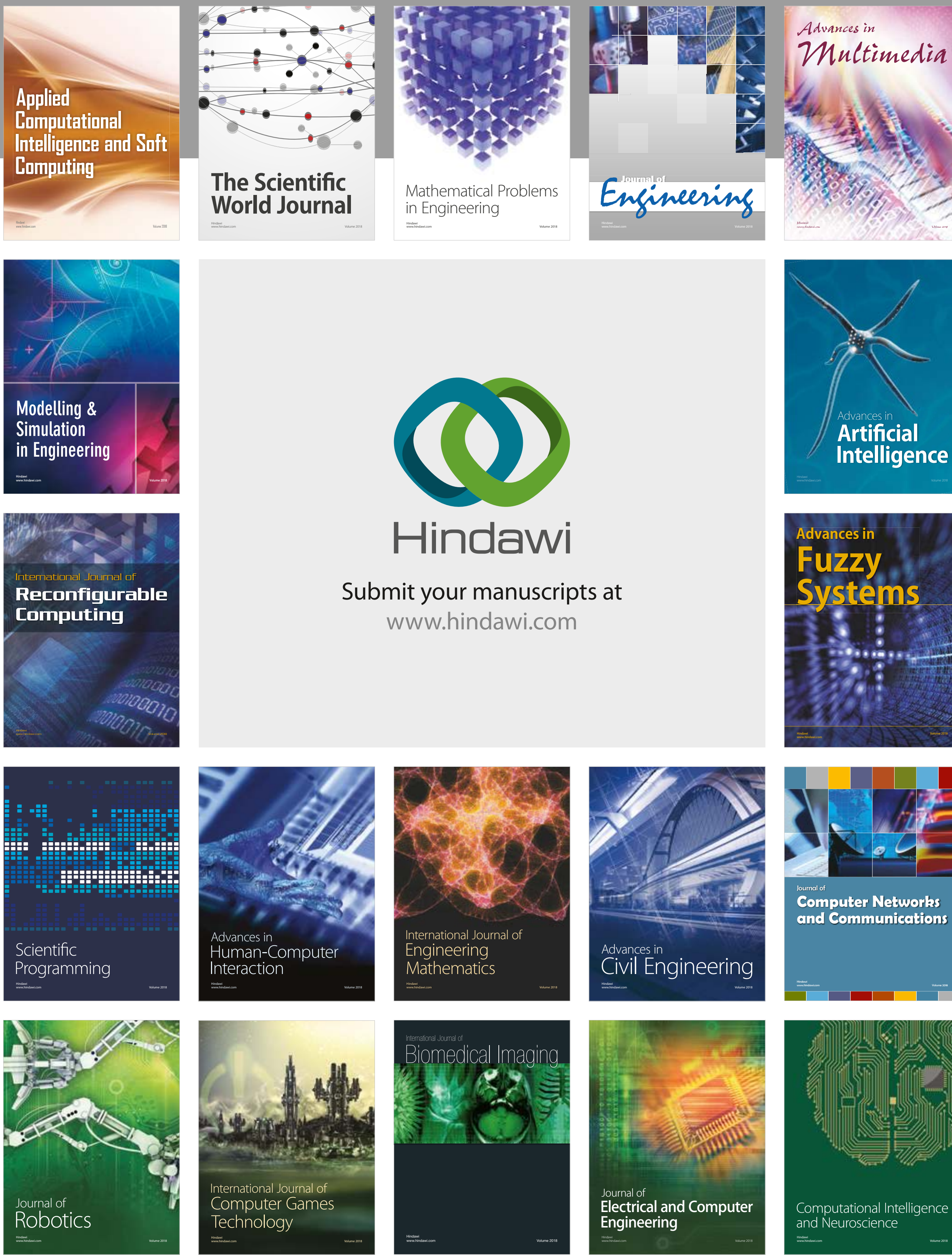
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