Design Optimization of Sewer System Using Particle Swarm Optimization

Praveen K. Navin and Y.P. Mathur

Abstract Particle swarm optimization (PSO) technique with new modification is applied in this paper for optimally determine the sewer network component sizes of a predetermined layout. This PSO technique is used for dealing with both discrete and continuous variables as requisite by this problem. A live example of a sewer network is considered to show the algorithm performance, and the results are presented. The results show the capability of the proposed technique for optimally solving the problems of sewer networks.

Keywords Sewer network · Particle swarm optimization · Optimal sewer design

1 Introduction

Sewer networks are an essential part of human society, which collect wastewater from residential, commercial and industrial areas and transports to wastewater treatment plant. Construction and maintenance of this large-scale sewer networks required a huge investment. A relatively small change in the component and construction cost of these networks, therefore leads to a substantial reduction in project cost. The design of a sewer network problem includes two sequential sub problems: (1) generation of the network layout and (2) optimal sizing of sewer network components. The component size optimization of sewer network problem consists of many hydraulic and technical constraints which are generally nonlinear, discrete and sequential. Satisfying such constraints to give an optimal design is often challenging even to the modern heuristic search methods. Many optimization techniques have been applied and developed for the optimal design of sewer networks, such as linear programming [1, 2], nonlinear programming [3, 4] and

P.K. Navin (✉) · Y.P. Mathur
Department of Civil Engineering, MNIT, Jaipur 302017, India
e-mail: navin.nitj@gmail.com

Y.P. Mathur
e-mail: ypmathur.ce@mnit.ac.in

M. Pant et al. (eds.), *Proceedings of Fifth International Conference on Soft Computing for Problem Solving*, Advances in Intelligent Systems and Computing 437, DOI 10.1007/978-981-10-0451-3_17

dynamic programming [5–7]. Evolutionary strategies, such as genetic algorithms [8, 9], ant colony optimization algorithms [10, 11], cellular automata [12] and particle swarm optimization algorithms [13], have received significant consideration in sewer network design problems. Recently, Ostadrahimi et al. [14] used multi-swarm particle swarm optimization (MSPSO) approach to present a set of operation rules for a multi-reservoir system. Haghighi and Bakhshipour [15] developed an adaptive genetic algorithm. Therefore, every chromosome, consisting of sewer slopes, diameters, and pump indicators, is a feasible design. The adaptive decoding scheme is set up based on the sewer design criteria and open channel hydraulics. Using the adaptive GA, all the sewer system's constraints are systematically satisfied, and there is no need to discard or repair infeasible chromosomes or even apply penalty factors to the cost function. Moeini and Afshar [16] used tree growing algorithm (TGA) for efficiently solving the sewer network layouts out of the base network while the ACOA is used for optimally determining the cover depths of the constructed layout.

In this paper, PSO algorithm with new modification is applied to get optimal sewer network component sizes of a predetermined layout.

2 Formulation of Sewer System Design

2.1 Sewer Hydraulics

In circular sewer steady-state flow is described by the continuity principle and Manning's equation which is

$$Q = VA \tag{1}$$

$$V = \frac{1}{n} R^{2/3} S^{1/2} \tag{2}$$

where Q = sewage flow rate, V = velocity of sewage flow, A = cross-sectional flow area, R = hydraulic mean depth, n = Manning's coefficient and S = slope of the sewer. Common, partially full specifications for circular sewer sections are also determined from the following equations:

$$K = QnD^{-8/3} S^{-1/2} \tag{3}$$

$$\theta = \frac{3\pi}{2} \sqrt{1 - \sqrt{1 - \sqrt{\pi K}}} \tag{4}$$

$$\left(\frac{d}{D}\right) = \frac{1}{2} \times \left(1 - \cos\frac{\theta}{2}\right) \tag{5}$$

$$R = \frac{D}{4}\left(\frac{\theta - \sin\theta}{\theta}\right) \tag{6}$$

where K = constant, D = sewer diameter, θ = the central angle in radian and (d/D) = proportional water depth. Equation (4) is applicable for K values less than ($1/\pi$) = 0.318 Saatci [17].

2.2 Sewer Design Constraints

For a given network, the optimal sewer design is defined as a set of pipe diameters, slopes and excavation depths which satisfies all the constraints. Typical constraints of sewer networks design are:

1. Pipe flow velocity: each pipe flow velocity must be greater than minimum permissible velocity to prevent the deposit of solids in the sewers and less than maximum permissible velocity to prevent sewer scouring. The minimum permissible velocity of 0.6 m/s and maximum velocity of 3.0 m/s have been adopted in the present paper.
2. Flow depth ratio: wastewater depth ratio of the pipe should be less than 0.8.
3. Choosing pipe diameters from the commercial list.
4. Pipe cover depths: maintaining the minimum cover depth to avoid damage to the sewer line and adequate fall for house connections. The minimum cover depth of 0.9 m and maximum cover depth of 5.0 m have been adopted.
5. Progressive pipe diameters: The diameter of ith sewer should not be less than the diameter of immediately preceding sewer.

The optimal design of a sewer system for a given layout is to determine the sewer diameters, cover depths and sewer slopes of the network in order to minimize the total cost of the sewer system. The objective function can be stated as

$$\text{Minimize}(C) = \sum_{i=1}^{N} (\text{TCOST}_i + \text{PC}_i) \tag{7}$$

where I = 1,…, N (total number of sewers), TCOST_i (total cost) = (Cost of sewer_i + Cost of manhole_i + Cost of earth work_i) and PC_i = penalty cost (it is assigned if the design constraint is not satisfied).

3 Particle Swarm Optimization (PSO)

Kennedy and Eberhart [18] were first to introduce particle swarm optimization technique in 1995. In PSO techniques, every problem solution is a flock of birds and denoted to the particle. In this technique, birds develop personal and social behaviour and reciprocally manage their movement towards a destination [13, 19].

Each particle is affected by these components: (i) its own velocity, (ii) the best location or position it has attained so far called particle best position and (iii) the overall best position attained by all particles called global best position. Initially, the group of particles starts their movement in the first iteration randomly, and then they try to search the optimum solution. The procedure can be described mathematically, as below [14, 20–22].

The current location of the *i*th particle with D-dimensions at *t*th iteration is indicated as

$$X_i(t) = \{x_{i1}, x_{i2}, x_{i3}, \ldots, x_{\mathrm{id}}\}^t \tag{8}$$

Earlier best position or location,

$$P_i(t) = \{p_{i1}, p_{i2}, p_{i3}, \ldots, p_{\mathrm{id}}\}^t \tag{9}$$

and velocity

$$V_i(t) = \{v_{i1}, v_{i2}, v_{i3}, \ldots, v_{\mathrm{id}}\}^t \tag{10}$$

Every particle's location in the search space is updated by

$$X_i(t) = X_i(t-1) + V_i(t) \tag{11}$$

where the new velocity

$$V_i(t) = \omega \cdot V_i(t-1) + c_1 \cdot R_1\{P_i(t) - X_i(t-1)\} + c_2 \cdot R_2\{P_g(t) - X_i(t-1)\} \tag{12}$$

where $i = 1, 2, \ldots, N$ (N denotes population size); $t = 1, 2, \ldots, T$ (T denotes a total number of iterations); ω = factor of inertia; R_1 and R_2 are the random values (which between 0 and 1); c_1 and c_2 are the learning or acceleration coefficients. $X_i(t)$ (location of every particle) is calculated by its earlier location $X_i(t-1)$ and its current velocity. $V_i(t)$ (particle's velocity) changes the location of the particles towards a better solution, at every iteration. $V_i(t-1)$ is the velocity from the earlier iteration, P_i is the best location of every particle and P_g is the best position or location ever found by any particle.

The inertia weights of each time interval (or iteration) $\omega(t)$ and acceleration coefficient (c_1 and c_2) are updated with these equations:

$$\omega(t) = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{T} \times t \tag{13}$$

$$c_1 = c_{1,\max} - \frac{c_{1,\max} - c_{1,\min}}{T} \times t \tag{14}$$

$$c_2 = c_{2,\max} - \frac{c_{2,\max} - c_{2,\min}}{T} \times t \tag{15}$$

where T = total number of iterations; $\omega_{\min}$ and $\omega_{\max}$ are the minimum and maximum inertia weights, and their values have been taken as 0 and 0.8, respectively, in the present problem; $c_{1,\max}$ and $c_{2\max}$ = maximum accelerations factors, their values have been taken as 2; $c_{1,\min}$ and $c_{2,\min}$ = minimum accelerations factors, their values have been taken as 0.5.

Particle velocities on every dimension are limited to minimum and maximum velocities.

$$V_{\min} \leq V_i \leq V_{\max} \tag{16}$$

The particle velocities are an important factor. $V_{\max}$ and $V_{\min}$ must be limited. Otherwise, the solution space may not be discovered precisely. $V_{\max}$ is generally considered about 10–20 % of the range of the variable on every dimension [19].

According to the above-mentioned Eqs. (11) and (12), a possible structure of the PSO algorithm is shown below.

1. Initialise a population of particles by randomly assigning initial velocity and location of every particle.
2. Calculate the optimal fitness function for every particle.
3. For every particle, compare the fitness value with the best particle (P_i) fitness value. If the current value is better than P_i, then update the position with the current position.
4. Calculate the best particle of the swarm with the best fitness value, if the best particle value is better than global best (P_g), then update the P_g and its fitness value with the location.
5. Determine new velocities for all the particles using Eq. (12).
6. Update new position of each particle using Eq. (11).
7. Repeat steps 2–6 until the stopping criterion is met.
8. Show the result given by the best particle.

Above-mentioned PSO algorithm deal with both discrete and continuous variables. PSO algorithm with discrete variables is requisite for the design of sewer networks.

4 Optimization of Sewer System

The live example (Sudarshanpura, Jaipur, India sewer network) is considered to check the above-proposed approach. The Sudarshanpura sewer network (Fig. 1) consists of 105 manholes and 104 pipes.

The following steps were used to optimize the component sizing of sewer system using PSO algorithm:

1. Start with first link ($i = 1$) of the first iteration.
2. Calculate constant value K,
    - If $K > 0.305$, then increase diameter.
3. If $K < 0.305$, then calculate sewer hydraulics.
4. Calculate invert levels of upstream and downstream nodes of a particular link.
5. Calculate cost of pipe, cost of manhole and cost of earthwork.
6. Calculate total cost of sewer network (TCOST).
7. Add the respective penalty cost (PC) in TCOST where constraints are violated.
8. Calculate feasible solution using PSO.
9. Check solutions obtained are feasible or not.
10. If feasible solution is not obtained increase iteration by 1 and go to step 1.
11. If feasible solution is obtained, then take output.
12. End.

The cost of pipe (RCC NP4 class), manhole and earth work were taken from Integrated Schedule of Rates, RUIDP [23].

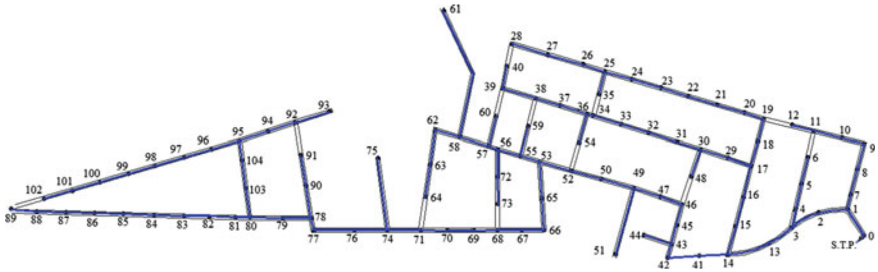

Fig. 1 Sudarshanpura sewer network

5 Results

The performance of the proposed PSO procedure for optimization of the sewer system is now tested against Sudarshanpura sewer network. The optimal results are obtained using 60 iterations and population size of 1000, respectively. The total cost of the sewer system using PSO approach was found to be Rs. 8.505×10^6 and 9.232×10^6 for the traditional design approach. Thus, there is 7.87 % reduction in total cost by applying PSO approach to the present problem. Table 1 shows the solution obtained by PSO approach.

Table 1 Results of the Sudarshanpura sewer network obtained by PSO

Pipe no.	Manhole no.		Pipe length (m)	Diameter (mm)	Slope (1 in.)	Design flow (m^3/s)	V_p (m/s)	d/D	Cover depths (m)	
	Up	Down							Up	Down
6	6	5	30	200	250	0.0004	0.254	0.093	1.120	1.145
13	12	11	20	200	60	0.0003	0.360	0.053	1.577	1.120
30	28	27	30	200	60	0.0004	0.413	0.065	1.350	1.120
38	35	25	12	200	250	0.0004	0.254	0.093	1.657	1.120
43	40	39	14	200	250	0.0004	0.254	0.093	1.120	1.406
48	44	43	30	200	60	0.0004	0.413	0.065	1.120	1.130
52	48	30	24	200	250	0.0005	0.279	0.108	1.874	1.120
55	51	49	72	200	250	0.0009	0.335	0.145	1.237	1.120
59	54	36	24	200	60	0.0005	0.454	0.076	1.120	1.125
62	59	55	30	200	250	0.0006	0.289	0.114	1.120	1.360
66	60	57	32	200	250	0.0006	0.295	0.118	1.120	1.568
69	61	58	143	300	250	0.0518	0.969	0.696	1.220	2.897
72	64	63	33	200	125	0.0007	0.386	0.104	1.120	1.124
79	73	72	30	200	250	0.0006	0.289	0.114	1.125	1.120
85	75	74	76	200	250	0.0010	0.340	0.149	1.120	1.229
99	89	88	30	300	250	0.0504	0.965	0.682	1.220	1.275
101	91	90	33	200	250	0.0008	0.326	0.139	1.120	1.142
103	93	92	36	200	250	0.0005	0.270	0.103	1.120	1.239
112	102	101	30	200	250	0.0008	0.316	0.132	1.120	1.135
5	5	4	30	200	250	0.0008	0.316	0.132	1.145	1.205
12	11	10	30	200	200	0.0008	0.350	0.130	1.130	1.120
29	27	26	30	200	250	0.0008	0.316	0.132	1.120	1.565
42	39	38	30	200	250	0.0006	0.287	0.113	1.406	1.221
71	63	62	33	200	250	0.0011	0.354	0.158	1.124	1.151
78	72	56	21	200	60	0.0011	0.586	0.113	1.120	1.335
98	88	87	30	300	250	0.0508	0.966	0.686	1.275	1.380
100	90	78	33	200	125	0.0013	0.470	0.143	1.161	1.120
104	92	94	30	200	250	0.0008	0.326	0.139	1.239	1.309
105	94	95	26	200	250	0.0012	0.362	0.164	1.309	1.408
111	101	100	30	200	250	0.0011	0.359	0.162	1.135	1.190
4	4	3	10	200	250	0.0009	0.332	0.143	1.205	1.180

(continued)

Table 1 (continued)

Pipe no.	Manhole no.		Pipe length (m)	Diameter (mm)	Slope (1 in.)	Design flow (m^3/s)	V_p (m/s)	d/D	Cover depths (m)	
	Up	Down							Up	Down
11	10	9	20	200	250	0.0013	0.370	0.170	1.120	1.150
28	26	25	27	200	250	0.0011	0.355	0.159	1.565	2.178
41	38	37	30	200	250	0.0011	0.358	0.161	1.380	1.120
70	62	58	24	200	60	0.0014	0.624	0.125	1.151	1.281
97	87	86	30	300	250	0.0511	0.967	0.690	1.380	1.320
110	100	99	30	200	70	0.0015	0.608	0.136	1.190	1.559
10	9	8	30	200	70	0.0015	0.607	0.135	1.391	1.120
27	25	24	30	200	80	0.0019	0.619	0.156	2.178	2.413
40	37	36	16	200	250	0.0013	0.376	0.175	1.151	1.120
68	58	57	33	300	250	0.0536	0.974	0.713	2.897	2.944
96	86	85	30	300	250	0.0515	0.968	0.693	1.465	1.220
109	99	98	30	200	80	0.0019	0.623	0.157	1.559	1.869
9	8	7	30	200	80	0.0019	0.622	0.157	1.830	1.120
26	24	23	30	200	100	0.0022	0.606	0.181	2.413	2.523
39	36	34	7	200	80	0.0019	0.626	0.159	1.125	1.158
65	57	56	8	300	250	0.0545	0.977	0.723	2.944	2.881
95	85	84	30	300	250	0.0519	0.969	0.697	1.220	1.270
108	98	97	30	200	100	0.0023	0.609	0.182	1.869	2.029
8	7	1	9	200	80	0.0020	0.633	0.161	1.273	1.120
25	23	22	30	200	100	0.0026	0.635	0.196	2.523	2.748
36	34	33	18	200	100	0.0023	0.615	0.185	1.158	1.188
64	56	55	25	300	250	0.0560	0.980	0.738	2.881	2.746
94	84	83	30	300	250	0.0523	0.971	0.700	1.275	1.220
107	97	96	30	200	100	0.0027	0.638	0.197	2.029	2.214
24	22	21	30	200	125	0.0030	0.612	0.222	2.748	2.863
35	33	32	30	200	100	0.0027	0.643	0.200	1.188	1.253
61	55	53	20	300	250	0.0570	0.982	0.749	2.746	2.896
93	83	82	30	300	250	0.0527	0.972	0.704	1.220	1.290
106	96	95	30	200	125	0.0030	0.614	0.223	2.214	2.419
23	21	20	30	200	125	0.0034	0.634	0.236	2.863	2.988
34	32	31	30	200	125	0.0031	0.619	0.226	1.253	1.128
92	82	81	30	300	250	0.0530	0.973	0.708	1.290	1.295
116	95	104	27	200	150	0.0046	0.647	0.287	2.419	2.529
115	104	103	27	200	150	0.0049	0.661	0.298	2.529	2.644
22	20	19	18	200	150	0.0036	0.606	0.255	2.988	3.043
33	31	30	30	200	125	0.0035	0.640	0.240	1.230	1.120
91	81	80	10	300	250	0.0532	0.973	0.709	1.295	1.270
114	103	80	27	200	200	0.0052	0.607	0.332	2.644	2.724
21	19	18	12	200	150	0.0040	0.624	0.269	3.043	2.928
32	30	29	22	200	150	0.0043	0.636	0.278	1.223	1.120
90	80	79	31	300	250	0.0588	0.985	0.771	2.724	2.758
20	18	17	30	200	150	0.0043	0.638	0.280	2.928	3.068

(continued)

Table 1 (continued)

Pipe no.	Manhole no.		Pipe length (m)	Diameter (mm)	Slope (1 in.)	Design flow (m^3/s)	V_p (m/s)	d/D	Cover depths (m)	
	Up	Down							Up	Down
31	29	17	30	200	150	0.0047	0.652	0.291	1.120	1.160
89	79	78	31	300	250	0.0592	0.986	0.776	2.758	2.587
19	17	16	30	200	250	0.0096	0.653	0.485	3.068	3.053
88	78	77	13	300	200	0.0606	1.091	0.719	2.587	2.717
18	16	15	30	200	250	0.0099	0.659	0.495	3.053	3.138
87	77	76	38	300	200	0.0611	1.092	0.724	2.717	2.842
17	15	14	30	200	250	0.0103	0.665	0.505	3.138	3.233
86	76	74	38	350	250	0.0616	1.028	0.597	2.842	2.949
84	74	71	34	350	250	0.0630	1.033	0.605	2.949	2.920
83	71	70	26	350	250	0.0635	1.035	0.608	2.920	2.939
82	70	69	26	350	250	0.0638	1.036	0.610	2.939	2.838
81	69	68	26	350	250	0.0642	1.037	0.612	2.838	2.722
77	68	67	22	350	250	0.0644	1.038	0.614	2.722	2.665
76	67	66	22	350	250	0.0647	1.039	0.616	2.665	2.713
75	66	65	30	350	250	0.0651	1.040	0.618	2.713	2.683
74	65	53	30	350	250	0.0655	1.041	0.620	2.683	2.663
60	53	52	30	400	250	0.1229	1.190	0.750	2.896	2.731
57	52	50	30	450	450	0.1234	0.957	0.740	2.731	2.573
56	50	49	30	450	450	0.1238	0.958	0.742	2.573	2.564
54	49	47	26	450	450	0.1251	0.959	0.748	2.564	2.207
53	47	46	26	450	450	0.1254	0.959	0.750	2.207	1.895
50	46	45	20	450	450	0.1258	0.960	0.752	1.895	2.214
49	45	43	20	450	450	0.1261	0.960	0.753	2.214	2.504
47	43	42	11	450	450	0.1266	0.960	0.756	2.504	2.388
46	42	41	30	450	450	0.1270	0.960	0.758	2.388	1.370
45	41	14	30	450	60	0.1274	2.130	0.416	1.625	1.370
16	14	13	30	450	400	0.1381	1.021	0.777	3.233	2.938
15	13	3	30	450	350	0.1384	1.084	0.733	2.938	2.719
3	3	2	23	500	400	0.1396	1.052	0.636	2.719	2.111
2	2	1	23	500	60	0.1399	2.177	0.377	2.407	1.420
1	1	0	30	500	80	0.1423	1.966	0.410	1.420	1.455

6 Conclusion

A particle swarm optimization with new modification was applied in this paper to the optimal solution of sewer system design problems. Using the PSO approach, the total cost of the sewer system was reduced by 7.87 % compared to the traditional design approach. The results indicated that the proposed approach is very promising and reliable, that must be taken as the key alternative to solve the problem of optimal design of sewer system.

References

1. Dajani, J.S., Gemmell, R.S., Morlok, E.K.: Optimal design of urban wastewater collection networks. J. Sanitary Eng. Div. **98**, 853–867 (1972)
2. Elimam, A.A., Charalambous, C., Ghobrial, F.H.: Optimum design of large sewer networks. J. Environ. Eng. **115**(6), 1171–1190 (1989)
3. Price, R.K.: Design of storm water sewers for minimum construction cost. In: 1st International Conference on Urban Strom Drainage. Southampton, UK, pp. 636–647 (1978)
4. Swamee, P.K.: Design of sewer line. J. Environ. Eng. **127**, 776–781 (2001)
5. Walsh, S., Brown, L.C.: Least cost method for sewer design. J. Environ. Eng. Div. **99**(3), 333–345 (1973)
6. Walters, G.A., Templeman, A.B.: Non-optimal dynamic programming algorithms in the design of minimum cost drainage systems. Eng. Optim. **4**, 139–148 (1979)
7. Li, G., Matthew, R.G.S.: New approach for optimization of urban drainage systems. J. Environ. Eng. **116**, 927–944 (1990)
8. Walters, G.A., Lohbeck, T.: Optimal layout of tree networks using genetic algorithms. Eng. Optim. **22**, 27–48 (1993)
9. Afshar, M.H.: Application of a genetic algorithm to storm sewer network optimization. Scientia Iranica **13**, 234–244 (2006)
10. Afshar, M.H.: Partially constrained ant colony optimization algorithm for the solution of constrained optimization problems: application to storm water network design. Adv. Water Resour. **30**, 954–965 (2007)
11. Afshar, M.H.: A parameter free continuous ant colony optimization algorithm for the optimal design of storm sewer networks: constrained and unconstrained approach. Adv. Eng. Softw. **41**, 188–195 (2010)
12. Guo, Y., Walters, G.A., Khu, S.T., Keedwell, E.: A novel cellular automata based approach to storm sewer design. Eng. Optim. **39**, 345–364 (2007)
13. Izquierdo, J., Montalvo, I., Pérez, R., Fuertes, V.S.: Design optimization of wastewater collection networks by PSO. Comput. Math Appl. **56**, 777–784 (2008)
14. Ostadrahimi, L., Mariño, M.A., Afshar, A.: Multi-reservoir operation rules: multi-swarm pso-based optimization approach. Water Resour. Manage **26**, 407–427 (2012)
15. Haghighi, A., Bakhshipour, A.E.: Optimization of sewer networks using an adaptive genetic algorithm. Water Resour. Manage **26**, 3441–3456 (2012)
16. Moeini, R., Afshar, M.H.: Sewer network design optimization problem using ant colony optimization algorithm and tree growing algorithm. In: EVOLVE-A bridge between probability, set oriented numerics, and evolutionary computation IV, pp. 91–105. Springer International Publishing (2013)
17. Saatci, A.: Velocity and depth of flow calculations in partially filled pipes. J. Environ. Eng. **116**, 1202–1208 (1990)
18. Kennedy, J., Eberhart, R.: Particle swarm optimization. In: IEEE International Conference on Neural Networks, IEEE Service Center, Piscataway, NJ, IV, Perth, Australia, pp. 1942–1948 (1995)
19. Shi, Y., Russell, E.: A modified particle swarm optimizer. In: IEEE International Conference on Evolutionary Computation, Anchorage, AK pp. 69–73 (1998)
20. Mu, A., Cao, D., Wang, X.: A modified particle swarm optimization algorithm. Nat. Sci. **1**, 151–155 (2009)
21. Al-kazemi, B., Mohan, C.K.: Multi-phase discrete particle swarm optimization. In: Proceeding of the Fourth International Workshop on Frontiers in Evolutionary Algorithms (2002)
22. Voss, M.S.: Social programming using functional swarm optimization. In: IEEE Swarm Intelligence Symposium, Indiana, USA, pp. 103–109 (2003)
23. Integrated Schedule of Rates: Rajasthan urban infrastructure development project (RUIDP), Government of Rajasthan (2013)