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An optimization procedure for the layout and component size optimization of sewer network

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Abstract: The optimal design of a sewer system, two sub-problems required to solve the optimal layout generation of a base network and optimal design of sewer component sizing simultaneously. This paper goals to acuaint a technique to solve the issue of sewer network layout and component size optimization. An algorithm generation of a predefined number of spanning trees is used to extract all prescribed number of sewer layouts from a base sewer network.The LQ (sum of the product of individual link length and its discharges of a layout) function is used to find the optimal sewer layouts from the generated layouts while the PSO (particle swarm optimization) algorithm is used to obtain the optimal component sizes of the selected layout. The proposed strategy is applied to address the Sudarshanpura sewer network (situated in Jaipur, India) problem.It has been observed that the optimal sewer layout for total system optimization is one where the LQ has the minimal value.

Keywords: Sewer networks;Layout optimization; PSO; Component Sizing

I. INTRODUCTION

A sewerage system is used to collect and transport wastewater from residential, commercial and industrial areas to sewage treatment plants through the sewers, manhole and other appurtenances of the network. Sewerage system is constructed to protect human health andthe environment. The design of a sewerage system consists of generating an appropriate sewer layout, sewer diameters, slope and other components that collectsewage and transport to the treatment plant with non-silting, non-scouring velocity. The optimal design of sewer network is a complex problem and the issue related to it are (i) different alternative layouts would have different discharges in sewers. When the discharge is high, the same diameter sewer may be laid on a flatter slope to get self-cleansing velocity. These flatter slopes may reduce the cost of excavation and cost of manholes; (ii) the minimum spanning tree provides a layout of minimum length; and (iii) the ground levels also play an important role as it can affect the depth of excavation andthe cost of manholes and earthwork.

It is necessary to investigate a large number of layouts for optimal sewer network design which a tough and time-consuming task. Reduction in the length of sewer line and depth of manholes leads toa substantial saving.

For this reason, Many researchers have attemptedto develop theoptimal design of sewer networks in recent years.Majority of the research work for the optimal design of sewer networksis restricted to the optimal design of network components.Only a few researchers have addressed the problemsassociated with layoutoptimization of sewersystems[1],[2], [3],[4],[5],[6],[7], [8], [9],[10],[11],[12][13],[14],[15].

The present work describes a method for the layout and component size optimizationofa sewer network.An algorithm generation of a predefined number of spanning trees is used to extract all prescribed number of sewer layouts from a base sewer network.After this, the optimal layout of a base network is selected where the LQ (sum of link length multiplied by its link discharge) value of the layout is minimal. The Particle swarm optimization (PSO) techniques are used to determine optimal sewer component sizes of pre-optimized sewer layout.The proposed method is applied to a sewer network problem and theresults are discussed and presented.The results show the ability of the proposed method to optimally solve the layout and component size determination of a sewer network problem.

II. SELECTION OF SEWER NETWORK LAYOUT

For the selection of optimal sewer network, it is initially required to have a layout generator procedure to generate all layout alternatives from a given base graph (network). In extracting a feasible layout from a base graph the following constraints need to be satisfied[14].(1) No cycle is accepted in the layout (spanning tree). (2) All manholes must be involved in the layout (tree).

The 'generation of a predetermined number of spanning trees' algorithm introduced by Navin & Mathur [14]determines all predetermined sewer layoutsfrom a base network. There are a large number oflayoutsavailable, and it is very tough to find the real optimal layout. Therefore, a strategy for the optimal layout selection is proposed. LQ_j is the sum of the product of individual link length and its discharges of the j^{th} layout and is calculated by Eq. 1.The LQ of each layout is calculated using Eq. 1, and the optimal layout of a base network is selected where the LQ(sum of the link length multiplied by its link discharge)value of the layout is minimal.

$$LQ_j = \sum_{i=1}^{N} L_{ij} \times q_{ij} \tag{1}$$

Where LQ_j = sum of the product of the individual link length and its discharges ofthe j^{th} alternative; L_{ij}= link length; q_{ij}= sewer discharge in the i^{th} link of thej^{th}layout; and N = total links in the j^{th} layout.

A test example (network 1) as shown in Fig. 1 is considered to check the applicability of the proposed algorithm.The network 1 consists of 6 manholes (nodes or vertices) and 10 links (edges), the outlet is located at the manhole number 4. The wastewater contribution (or nodal contribution) at each node of the network 1 is given in table 1. The 'generation of a predetermined number of spanning tree' algorithm is applied to find all possible layouts of a network 1.The top 4 layouts of the Network 1 in order of increasing *LQ*are shown in Fig. 2 (a to d). *LQ*is calculated by using Eq.1 for all layouts.

Table 1. Nodal wastewater contribution for network 1

Node No.	1	2	3	4	5	6
Flow Contribution (l/s)	20	15	18	0	17	14

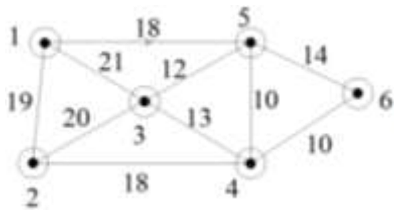

Fig. 1. Base layout of network 1

(a) LQ=1374

(b) LQ=1536

(c) LQ=1554 (d) LQ=1599

Fig. 2. Top 4 layouts according to ascending order of *LQ* for Network 1

III. PARTICLE SWARM OPTIMIZATION

Kennedy and Eberhart [16]introduced particle swarm optimization (PSO) algorithm in 1995; the method is based on the social behaviorof aflock of birds.In the PSO algorithm, eachpotential solution is a flock of birds and is mentioned to as a particle: in which, birds develop personal and some social behavior, and manage their movementtowards a food location or destination[17][18][23][24].The three parameters, whichaffect to each particle (a) particle's own movement, (b) particle's acquired best position so far, and (c) Global best position acquired by particle among allparticles[19].

The process firstly starts with a swarm of theparticle, in which every particle contains a contender solution to the problem that is generated randomly, and then the particles search the optimal solution by iteration.

Suppose $x_i(t) = \{x_{i1}(t), x_{i2}(t), x_{i3}(t), \ldots, x_{im}(t)\}$ is the current position of the i^th particle in m dimension at the t^th iteration, $v_i(t) = \{v_{i1}(t), v_{i2}(t), v_{i3}(t), \ldots, v_{im}(t)\}$ is the i^th particle flying velocity, and the best position of the i^th particle reached so far is,$y_i(t) = \{y_{i1}(t), y_{i2}(t), y_{i3}(t), \ldots, y_{im}(t)\}$.

Each particle's position in the search space is updated by

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{2}$$

The particle'svelocity is updated by

$$v_i(t+1) = \omega.\, v_i(t) + c_1 \cdot \mathrm{rand}_1\{y_i(t) - x_i(t)\} + c_2 \cdot \mathrm{rand}_2\{y_g(t) - x_i(t)\} \tag{3}$$

Where, i=1, 2,. . ., P (P is the total number of particles in a group); t=1, 2, ..., t_{max} (t_{max} is the total number of iterations); ω = inertia weight (which controls the impact of the velocity); rand_1 and rand_2 are the generated random numbers (between 0 and 1); c_1 and c_2 are the acceleration coefficients, y_i is the best position of a particle, and y_g is the best position ever found by any particleupto thet^th iteration.

The inertia weights of each time interval or iterationω(t) along with acceleration coefficients (c_1 and c_2) are updated with the following equations:

$$\omega(t) = \omega_{\min} + \frac{\omega_{\max} - \omega_{\min}}{t_{\max}} \times \left(t_{\max} - t\right) \tag{4}$$

$$c_1 = c_{1,\min} + \frac{c_{1,\max} - c_{1,\min}}{t_{\max}} \times \left(t_{\max} - t\right) \tag{5}$$

$$c_2 = c_{2,\min} + \frac{c_{2,\max} - c_{2,\min}}{t_{\max}} \times \left(t_{\max} - t\right) \tag{6}$$

Where t_{max} is the total number of iterations; ω_{max} is the maximumand ω_{min} is the minimum inertia weights, and their values have been taken as 0.7 and 0.2, respectively; $c_{1,\,max}$ and $c_{2,\,max}$ are the maximum accelerations, and their values have been taken as 2; $c_{1,min}$ and $c_{2,min}$ are the minimum accelerations, and their values have been taken as 0.5 in present problem.

In each dimension,the particle velocityis limited to maximum and minimumvelocitiesto restrict excessive roaming of particles beyond the search space.

$$v_{\min} \le v_i \le v_{\max} \tag{7}$$

v_{max} is generally fixed to about 10-20% of the range of the variable rangein every dimension [20]whereasv_{min} is suitably selectedto prevent stagnancy of the particles exploration of a search space.

The adjustable parameters v_{max}, v_{min}, ω_{max}, ω_{min}, c_1, and c_2 must be fixed according to the problem. These adjustable parameters should be adjusted by trial and error, according to the sensitivity of the problem and the model performance. Furthermore, these adjustable parameters, the total number of iteration and particles affect the final solution. Normally, the searching process is dismissed after a predefined number of iterations or when the best solution of the objective function remains unchanged for a specific number of consecutive iterations.The simplified representation of the PSO algorithm is shown in Fig. 3.

IV. SEWERAGE SYSTEM DESIGN

4.1 Sewer hydraulics

In a circular sewer, water flows either full or partially full. The hydraulics of circular sewer for running full condition is given by the following equations:

$$V = \frac{1}{n} R^{2/3} S^{1/2} \tag{8}$$

Where V = velocity of sewage flow, n = Manning's roughness coefficient, R = hydraulic mean depth, and S = sewer slope.
The hydraulics of circular sewer for running partially full condition is by the following equations:

$$\theta = \frac{3\pi}{2}\sqrt{1-\sqrt{1-\sqrt{\pi K}}} \tag{9}$$

$$K = QnD^{-8/3}S^{-1/2} \tag{10}$$

$$\left(\frac{d}{D}\right) = \frac{1}{2} \times \left(1-\cos\frac{\theta}{2}\right) \tag{11}$$

Where K = constant, calculated using equation 9; D = sewer diameter; (d/D) = proportional water depth; and θ = the central angle from the center of the section to the water surface (in radian). Equation 10 is applicable for K values less than (1/π) = 0.318 Saatci[21].

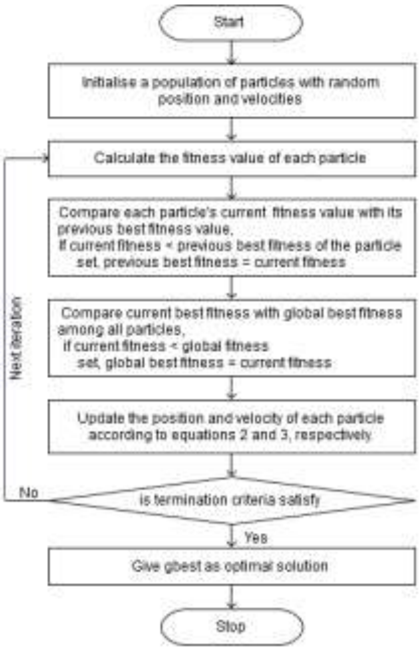

Fig. 3. Flow chart for PSO algorithm

4.2 Sewer design formulation

For a givensewer network, the optimal design of a sewer system is to determine the feasible sewer diameters, sewer slopes and excavation depths of the network in order to minimize the total cost of the sewer system.
The objective function selected in this work is:

$$\text{Minimize } C = \sum_{i=1}^{N} (TCOST_i + PC_i) \tag{12}$$

Where C = cost function of sewer network; i = 1, 2, …., N (N is the total number of sewers);$TCOST_i$ (total cost) = {(Cost of sewer)$_i$+ (Cost of earth work)$_i$+ (Cost of manhole)$_i$}; and PC_i = penalty cost (It is assigned if the design constraintsareviolated) for the ith sewer.

$$PC_i = (PCD_{\max})_i + (PV_{\min})_i + (PV_{\max})_i \tag{13}$$

Where $(PCD_{max})_i$is penalty due to maximum cover depth, $(PV_{min})_i$ is penalty due to minimum velocity, and $(PV_{max})_i$ is penalty due to maximum velocity for the ith link.

Following constraints have been considered:

1. Flow velocity: Velocity in each sewer must be greater than theminimum permissible velocity(self-cleansing velocity to avoid the deposit of solids) and less than the maximum allowablevelocity(to prevent sewerscouring). The minimum permissiblevelocity(V_{min})of 0.6 m/s and maximum velocity(V_{max})of 3.0 m/shas been adopted in the current paper.
2. Proportion flow depth: proportion wastewater depth in sewers should be less than 0.8.
3. Sewer diameter: Sewer diameters should be one of the available sewer diameters.
4. Sewer cover depths: maintaining the minimum cover depth to avoid damage to the sewer line. The minimum cover depth(CD_{min}) of0.9 m and maximum cover depth (CD_{max})of 5.0 m has been adopted in the current paper.
5. Progressive sewer diameters: The diameter of ith sewer should not be less than the diameter of sewers terminating at the manhole from where the ith sewer is starting.

V. OPTIMIZATION OF SEWER SYSTEM BY PSO

The second example (Sudarshanpura sewer network) as shown in Fig. 4has been considered for the optimal designby using the proposed method.The Sudarshanpura sewer network (Network 2) collects only domestic wastewater from the Sudarshanpura residential colony, Jaipur, India through gravity. The base Network 2 consists of 105 manholes (nodes or vertices) and 116 links (edges), Sewage treatment plant (outlet) is located at node number 0.The Sudarshanpura sewer network problem is solved in two stages. By Using 'Generation of a predetermined number of spanning trees' algorithm and LQ function (Eq. 1) in the first sub-problem (layout optimization), the optimum layout is determined by a base network 2. After this, the PSO algorithm is applied to the second sub-problem to design the sewer network component sizes.The processes of sewer component size optimization with PSO algorithm are shown in Fig. 5. The cost of sewer (RCC NP4 class), manhole, and earthwork were taken from Schedule of Rates [22].

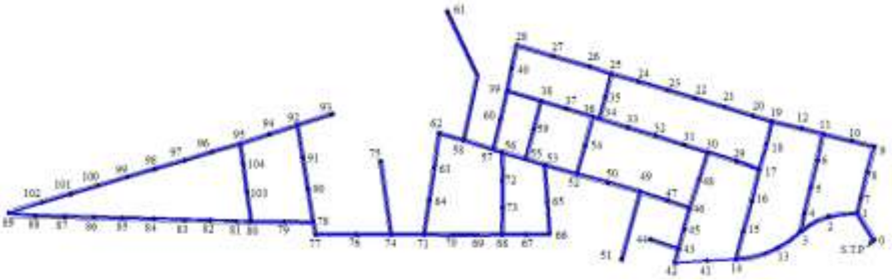

Fig. 4. Base network of Sudarshanpura (network 2)

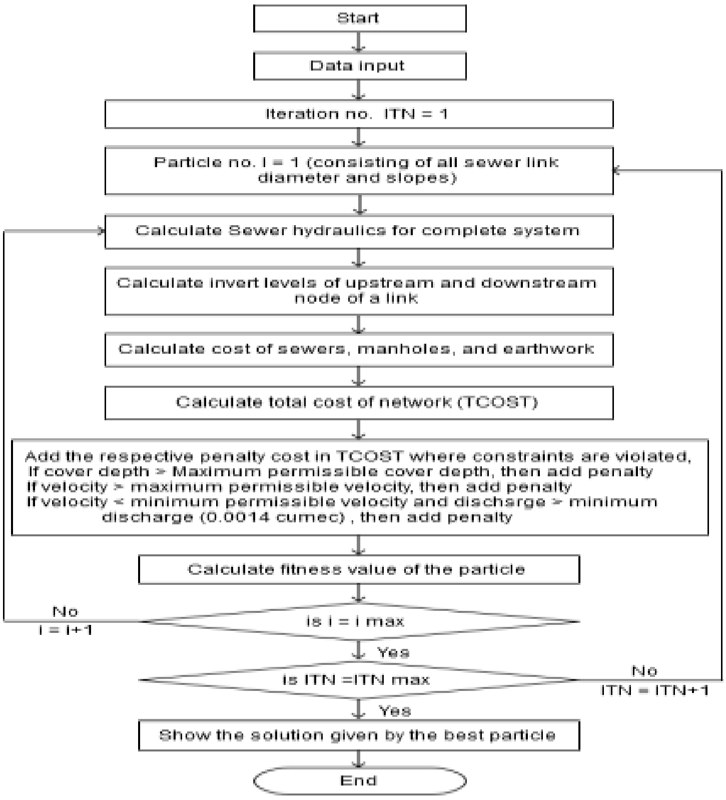

Fig. 5. Sewer component size optimization procedure using PSO

VI. RESULTS

Table 2 shows the top 10 optimal layouts in order to increasing LQ as obtained by the above proposed method; andit'srespective optimal construction costs as obtained by the PSO techniques. The results were obtained using swarm size 500 and 80iterations respectively, for each sewer layout.Table 2 shows that the optimal layout (LQ = 102321) has the minimumcost Rs. 8.432×10^{6}as shown in Fig. 6;and 2nd minimum cost is Rs. 8.527×10^{6}, obtained in2nd alternative layout (LQ= 102340) as shown in Fig. 7.Table 2 clearly shows that the number of alternative layouts has given near to the minimum cost. These alternative layouts may provide options to choose near optimal layout according to field condition.

Table 2. LQ value vs. optimal cost of a layout

S. No.	LQ	Optimal Cost (Rupees)
1	102321	8432775
2	102340	8527586
3	102356	8563060
4	102491	8583150
5	102504	8591171
6	102539	8628912
7	102583	8646994
8	104191	8713802
9	104404	8912218
10	104492	9027678

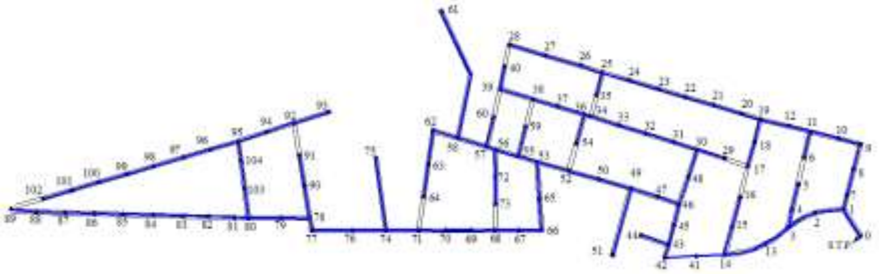

Fig. 6. Optimal sewer layout of network 2

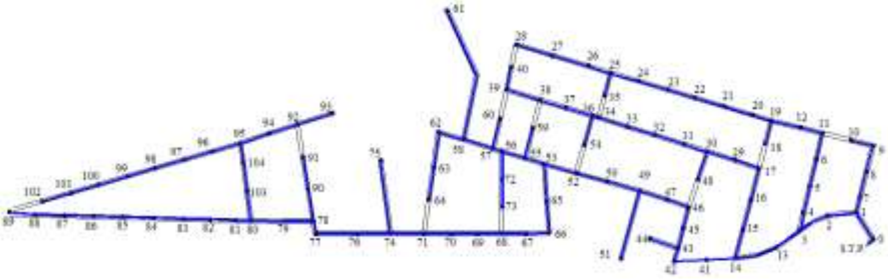

Fig. 7. Second best layout of network 2

The optimal sewer layout of a network 2 as shown in Fig. 6 is selected for thedetailed design. Fig. 8 shows that the total optimal cost obtained with the PSO algorithm against the swarm sizes for different iterations. The best solution produced when swarm size and iterations are 500, and 80, respectively. Table 3 shows the detailed results obtained by PSO approach.

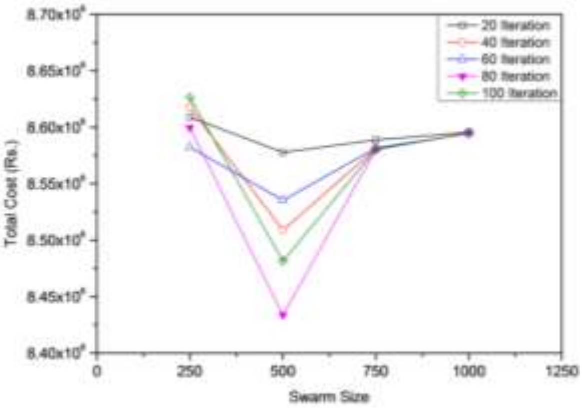

Fig. 8. Variation of the optimal cost with swarm sizes at different iterations

Table 3. Detailed results of the optimal sewer network obtained by PSO

Pipe no.	Node no.		Length (m)	Diameter (mm)	Slope (1 in)	Design flow (cumec)	vp (m/s)	d/D	Cover Depths (m)	
	Up	Down							Up	Down
5	5	4	30	200	250	0.0004	0.254	0.09	1.12	1.18
7	6	11	30	200	250	0.0004	0.254	0.09	1.12	1.245
18	16	15	30	200	250	0.0004	0.254	0.09	1.12	1.205
20	17	18	30	200	250	0.0006	0.289	0.11	1.12	1.3
21	18	19	12	200	250	0.0009	0.335	0.14	1.3	1.543
30	28	27	30	200	250	0.0004	0.254	0.09	1.73	1.12
32	29	30	22	200	250	0.0004	0.254	0.09	1.12	1.458
38	35	25	12	200	250	0.0004	0.254	0.09	1.657	1.12
43	40	39	14	200	250	0.0004	0.254	0.09	1.12	1.406
48	44	43	30	200	250	0.0004	0.254	0.09	1.49	1.12
55	51	49	72	200	250	0.0009	0.335	0.14	1.237	1.12

59	54	36	24	200	60	0.0005	0.454	0.08	1.12	1.125
62	59	55	30	200	250	0.0006	0.289	0.11	1.12	1.36
66	60	57	32	200	250	0.0006	0.295	0.12	1.12	1.568
69	61	58	143	300	250	0.0518	0.969	0.7	1.22	2.897
72	64	63	33	200	250	0.0007	0.304	0.12	1.248	1.12
79	73	72	30	200	250	0.0006	0.289	0.11	1.125	1.12
85	75	74	76	200	250	0.001	0.34	0.15	1.12	1.229
99	89	88	30	300	250	0.0504	0.965	0.68	1.22	1.275
101	91	90	33	200	250	0.0008	0.326	0.14	1.12	1.142
103	93	92	36	200	250	0.0005	0.27	0.1	1.12	1.239
112	102	101	30	200	250	0.0008	0.316	0.13	1.12	1.135
4	4	3	10	200	250	0.0005	0.279	0.11	1.18	1.155
17	15	14	30	200	250	0.0008	0.316	0.13	1.205	1.3
29	27	26	30	200	250	0.0008	0.316	0.13	1.12	1.565
42	39	38	30	200	250	0.0006	0.287	0.11	1.406	1.221
71	63	62	33	200	250	0.0011	0.354	0.16	1.12	1.147
78	72	56	21	200	125	0.0011	0.456	0.14	1.12	1.153
98	88	87	30	300	250	0.0508	0.966	0.69	1.275	1.38
100	90	78	33	200	60	0.0013	0.605	0.12	1.142	1.387
104	92	94	30	200	250	0.0008	0.326	0.14	1.239	1.309
105	94	95	26	200	250	0.0012	0.362	0.16	1.309	1.408
111	101	100	30	200	250	0.0011	0.359	0.16	1.135	1.19
28	26	25	27	200	250	0.0011	0.355	0.16	1.565	2.178
41	38	37	30	200	100	0.0011	0.491	0.13	1.221	1.141
70	62	58	24	200	60	0.0014	0.624	0.13	1.147	1.277
97	87	86	30	300	250	0.0511	0.967	0.69	1.38	1.32
110	100	99	30	200	70	0.0015	0.608	0.14	1.19	1.559
27	25	24	30	200	80	0.0019	0.619	0.16	2.178	2.413
40	37	36	16	200	250	0.0013	0.376	0.18	1.151	1.12
68	58	57	33	300	250	0.0536	0.974	0.71	2.897	2.944
96	86	85	30	300	250	0.0515	0.968	0.69	1.465	1.22
109	99	98	30	200	80	0.0019	0.623	0.16	1.559	1.869
26	24	23	30	200	100	0.0022	0.606	0.18	2.413	2.523
39	36	34	7	200	80	0.0019	0.626	0.16	1.125	1.158
65	57	56	8	300	250	0.0545	0.977	0.72	2.944	2.881
95	85	84	30	300	250	0.0519	0.969	0.7	1.22	1.27
108	98	97	30	200	100	0.0023	0.609	0.18	1.869	2.029
25	23	22	30	200	100	0.0026	0.635	0.2	2.523	2.748
36	34	33	18	200	100	0.0023	0.615	0.19	1.158	1.188
64	56	55	25	300	250	0.056	0.98	0.74	2.881	2.746
94	84	83	30	300	250	0.0523	0.971	0.7	1.275	1.22
107	97	96	30	200	100	0.0027	0.638	0.2	2.029	2.214
24	22	21	30	200	125	0.003	0.612	0.22	2.748	2.863
35	33	32	30	200	100	0.0027	0.643	0.2	1.188	1.253
61	55	53	20	300	250	0.057	0.982	0.75	2.746	2.896
93	83	82	30	300	250	0.0527	0.972	0.7	1.22	1.29
106	96	95	30	200	125	0.003	0.614	0.22	2.214	2.419
23	21	20	30	200	125	0.0034	0.634	0.24	2.863	2.988
34	32	31	30	200	125	0.0031	0.619	0.23	1.253	1.128
92	82	81	30	300	250	0.053	0.973	0.71	1.29	1.295
116	95	104	27	200	150	0.0046	0.647	0.29	2.419	2.529
115	104	103	27	200	150	0.0049	0.661	0.3	2.529	2.644
22	20	19	18	200	150	0.0036	0.606	0.26	2.988	3.043
33	31	30	30	200	125	0.0035	0.64	0.24	1.23	1.12

91	81	80	10	300	250	0.0532	0.973	0.71	1.295	1.27
114	103	80	27	200	200	0.0052	0.607	0.33	2.644	2.724
14	19	12	30	200	150	0.0049	0.661	0.3	3.043	3.133
52	30	48	24	200	150	0.0041	0.631	0.27	1.458	2.468
51	48	46	30	200	150	0.0047	0.652	0.29	2.468	2.673
90	80	79	31	300	250	0.0588	0.985	0.77	2.724	2.758
13	12	11	20	200	200	0.0052	0.604	0.33	3.133	2.443
89	79	78	31	300	250	0.0592	0.986	0.78	2.758	2.587
12	11	10	30	200	200	0.0061	0.633	0.36	2.443	2.433
88	78	77	13	300	200	0.0606	1.091	0.72	2.587	2.717
11	10	9	20	200	200	0.0065	0.645	0.37	2.433	2.483
87	77	76	38	300	200	0.0611	1.092	0.72	2.717	2.842
10	9	8	30	200	200	0.0068	0.651	0.38	2.483	1.933
86	76	74	38	300	200	0.0616	1.093	0.73	2.842	2.987
9	8	7	30	200	250	0.0072	0.608	0.42	2.085	1.12
84	74	71	34	300	200	0.063	1.096	0.74	2.987	2.992
8	7	1	9	200	250	0.0073	0.61	0.42	1.349	1.12
83	71	70	26	300	200	0.0635	1.098	0.75	2.992	3.037
82	70	69	26	300	200	0.0638	1.098	0.75	3.037	2.962
81	69	68	26	300	200	0.0642	1.099	0.75	2.962	2.872
77	68	67	22	300	200	0.0644	1.099	0.76	2.872	2.837
76	67	66	22	300	200	0.0647	1.1	0.76	2.837	2.907
75	66	65	30	300	200	0.0651	1.101	0.76	2.907	2.907
74	65	53	30	300	200	0.0655	1.101	0.77	2.907	2.917
60	53	52	30	400	250	0.1229	1.19	0.75	2.917	2.752
57	52	50	30	400	250	0.1234	1.19	0.75	2.752	2.647
56	50	49	30	450	450	0.1238	0.958	0.74	2.647	2.638
54	49	47	26	450	450	0.1251	0.959	0.75	2.638	2.281
53	47	46	26	450	450	0.1254	0.959	0.75	2.281	1.969
50	46	45	20	450	450	0.1305	0.963	0.78	2.673	2.992
49	45	43	20	450	450	0.1307	0.963	0.78	2.992	3.282
47	43	42	11	450	450	0.1313	0.963	0.78	3.282	3.166
46	42	41	30	450	400	0.1316	1.016	0.74	3.166	2.156
45	41	14	30	450	400	0.132	1.016	0.75	2.156	1.476
16	14	13	30	450	125	0.1332	1.631	0.52	1.5	1.37
15	13	3	30	450	100	0.1335	1.778	0.49	1.375	1.37
3	3	2	23	450	200	0.1343	1.359	0.6	1.92	1.37
2	2	1	23	450	250	0.1346	1.242	0.64	2.648	1.37
1	1	0	30	450	80	0.1423	1.965	0.48	1.37	1.405

VII. CONCLUSIONS

In this paper, an optimization procedure is introduced for the optimal layout and component size determination of a sewer network. An algorithm generation of a predefined number of spanning trees is used to determine all prescribed number of sewer layouts from a base sewer network. An LQ function is used to find the optimal sewer layout from the generated layouts. After the optimal layout is determined, a particle swarm optimization (PSO) algorithm is applied to determine the optimal component sizes of the selected layout. By applying an optimization procedure during the design of a sewer system substantial cost savings can be realized. The result showed that the optimal sewer layout has obtained minimum total cost, and a number of alternative layouts have near to optimal total cost.

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