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Layout Optimization of Sewer Networks by Adaptive Genetic Algorithmin A Hybrid Model

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Abstract: The problem of optimal layout is one of the most difficult problems. This is due to the large size of the search space, which expands rapidly as the size of the network increases. This paper introduces an adaptive procedure to improve the efficiency of genetic algorithm (GA) formulation in GA-TGA optimization model of the optimum layout design of sewer networks. Adaptive strategy helps the designer develop adaptive genetic algorithms in which method operators are systematically adapted to the constraints of the layout problem. The adaptive selection operator keeps the genetic algorithm in feasible region of the search space and consequently improve the performance of optimization in terms of speed. The formulation of selection and crossover lead to not need to discard or repair unfeasible solutions or apply penalty factors to the cost function as commonly used in the principles of genetic algorithms. Four different selection methods will be used with the GA. In MATLAB code, the optimization model implemented. Benchmark example and case study of sewer networks are used to test the present method. This method has proven to be effective in terms of solution optimality and the resulting convergence characteristics. Additionally, the method proves itself capable of finding an optimal, or near optimal solution.

Key words: Sewer networks, genetic algorithms, optimization, case study, fitness function

INTRODUCTION

Sewer networks are the basic infrastructure of urban cities and have a direct influence on public health. The task of building a new sewer system is a very expensive and difficult task especially in densely populated cities. Therefore, the issue has prompted engineers and researchers to develop optimization methods to obtain the most effective and efficient designs in terms of cost.

To find optimum sewer layout “system layout” is surely not an easy work for engineers. The difficulty is mainly due to two important factors: the complexity of the system’s environment and the huge number of possible design alternatives. Particularly in the large networks necessary for urban sewer system, manual calculation limits the evaluation of alternatives. This has inspired many computerized optimization model studies. Some researchers, have addressed the problem of layout geometry determination of networks using different optimization methods (Mays *et al*., 1976; Rowell and Barnes, 1982; Morgan and Goulter, 1985; Walski, 1985; Walters, 1992; Walters and Lohbeck, 1993; Davidson and Goulter, 1995;Walters and Smith, 1995; Davidson, 1999; Geem *et al*., 2000; Hassan *et al*., 2018).

Genetic algorithms are best suited to solving combinatorial optimization problems with very large solution spaces which cannot be solved using more conventional optimization methods. The GAs were originally conceived by Holland (1975) and have since been further developed by De Jong (1975), Goldberg (1989) and subsequently by many others (Miettinen *et al*., 1999). The use of genetic algorithms for effective and efficient research of the optimal layout solution for sewer network is governed by several factors such as coding type, fitness function, size of population, three main operators (choice, mating and mutation), penalty method, number of generation and finally, the most important is the size of the search space. This paper proposed an adaptive procedure to improve the efficiency of genetic algorithm formulation to reduce the search space. A model, GA-TGA, based on the proposed methodology is developed and first tested and verified for its efficiency and effectiveness on two previously benchmark problems networks (Hassan and Atiyah, 2019). Here, it is applied to the optimal layout design of case study in Karbala city, Iraq. The results obtained indicate that the modified GA with reduction in search space proposed herein is effective, especially for large practical networks.

ADAPTIVE GENETIC ALGORITHM FORMULATION

The genetic algorithm dates back to the late 1970's in Holland (1975) work such as evolutionary models. Its popularity has grown considerably since then and there are many engineering applications now. The algorithm uses crossover operators and mutation to move from one generation to the next to create solutions and the selection operator works to select individuals from generation to

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next. Genetic algorithms belong to a category of powerful research techniques that rely on genetic inheritance and natural selection in Darwinian metaphor. These algorithms maintain a finite memory of individual points on the search landscape known as the "population". Typically, members of the population are represented as a string, each of which has a standard value associated with it that reflects its quality or fitness. The research may seem to be a iterative application to a number of operators such as selection, crossover and mutation, the goal is to produce progressive individuals gradually. One of the larger drawbacks of genetic algorithms is that they require a large number of function evaluations to achieve convergence. Each functional evaluation requires a complete simulation of the system for a long time, a process that is highly cost-effective. This concludes that GA is a time-consuming optimization system. It can take an improved runtime for a large distribution system to take up to a few days on a modern personal computer. Various reasons can be stated why long running times may be problematic.

In the present study, an attempt is made to improve GA for the design layout of practical networks, by increasing its efficiency and effectiveness. In the adaptive GA, a integer representation, instead of using only the basic selection method, four different selection methods are used, simple objective function, order crossover method and a one gene mutation operator. A methodology based on critical path method is suggested herein to reduce the search space. The GA-TGA model is developed using MATLAB code.

The improved GA formulation was achieved by using different selection methods providing an improvement compared with the simple GA. As follows, a brief description of the four selection methods.

Roulette Wheel Selection (RWS): The roulette wheel is the simplest and traditional random selection method proposed by the Holland (1975). It is classified under a proportional selection as individuals select on the basis of a probability proportionate with their fitness. Assigned for each individual a part on the roulette wheel. The size of each part in the roulette wheel is proportional to the value of individual's fitness, The higher the value, the greater the part (Hassan, 2019):

$$p_i = \frac{f_i}{\sum_{j=1}^{n} f_j} \tag{1}$$

- **Stochastic Universal Sampling (SUS):** Stochastic Universal Sampling is introduced by Baker (1987), is quite similar to Roulette wheel selection. However, instead of spinning the roulette wheel n times as described in Roulette Wheel Selection, in this technique one can spin the Roulette Wheel just once, but after determining n points in the Wheel, where n is a population size. Then choose n chromosomes that situated in front of the determined points
- **Exponential Rank Selection (ERS):** This is based on the chromosomes' rank instead of their fitness. The rank of 1 is granted for the worst chromosome, while the best chromosome is given the rank of n. Thus, based on its rank, each chromosome (i) has the probability of being selected given the expression (Jebari and Madiafi, 2013):

$$p(i) = 1.0 \times e^{\left(\frac{-\mathrm{rank}(i)}{c}\right)} \tag{2}$$

Where:

$$c = \frac{\left(2n \times (n-1)\right)}{\left(6(n-1)+n\right)} \tag{3}$$

- **Random Selection (RMS):** In this method parents are randomly selected from the current population. There is no strategy for selection pressure to certain individuals and therefore prefer to avoid this method usually
- **GA-TGA model:** The GAs are often used in combination with a problem-specific or local search procedure, especially in commercial applications (Goldberg and Voessner, 1999). The goal of using a problem specific search method is to improve the efficiency of the GA, either in terms of the time required to find a good solution or the quality of the solution found. Early hybrid GAs were introduced by Smith (1985) and Grefenstette *et al.* (1985) are commonly used today in serious GA applications (Goldberg and Voessner, 1999)

The GA-TGA a technique combined genetic algorithm with tree growing algorithm, which uses a suitable growth algorithm TGA to avoid the problems associated with configuring of infeasible solutions, the following is a brief description of the model:

- **Coded the design variable:** This coded string is similar to the structure of a chromosome of genetic code. A selected mapping between the coded sub-strings and the design variables associates the artificial genetic code with a pipe network design
- **Generation of initial population by using TGA:** The trees produced will on average be biased towards those which diverge from a root node specified on the base graph. This is a useful feature of the algorithm as it closely mimics the characteristics of the natural plant growth and of most engineering tree networks involving flows

- **Fitness function:** For each layout in the population will be find the fitness, which is represented the inverse of the objective function of each layout. Walters and Smith (1995) suggested a simplified cost function to found the cost of layout based on the length and concave function of the flow rate per pipe, as shown follows:

$$\text{Fitness function} = 1/\text{objective function}$$

$$\text{Total cost} = \sum_{i=1}^{m} l_i \sqrt{Q_i} \qquad (4)$$

  where, total cost is the layout objective function, L is sewer length and Q is accumulated sewer flow rate that is indirectly obtained with the layout configuration
- Generation of a new population using the selection, crossover and mutation operators. They occur with some specified probability
- **Production of successive generations:** A new generation is produced when using the above three operators in steps 3 and 4. The GA repeats the process to generate successive generations. The least cost strings are stored and updated as cheaper cost alternatives are generated

APPLICATIONS

The applicability and efficiency of the formulations described in the previous section are tested in this section against benchmark example in the literature and the real case study. The first example to be considered is that of a simple network shown in Fig. 1 proposed and solved by Walters and Smith (1995) using evolutionary programing. More details about this example are found in the cited reference.

Figure 2 shows the typical convergence curve for a number of generations during the evolutionary process to reach the optimal solution cost by GA-TGA method with the RWS, ERS,SUS and RMS selection methods respectively, for directed base graph of the benchmark example.

The results were obtained with an order crossover method (Pc = 0.9) and a one gene mutation per chromosome with probability of mutation Pm = 0.5. As expected, the number of generations required to reach the final solution is improved by using different methods of selection. The optimum objective function of solution 5218 units was obtained with the Exponential Rank Selection (ERS) method, within 306 generations this is the best and fastest method of selection. As for the RWS method, here their little disparity in costs because total cost for each individual in population are close, so the chance is equal.RMS selection method the result of thismethod show that the data are irregular so this method do not work with the proposed model.

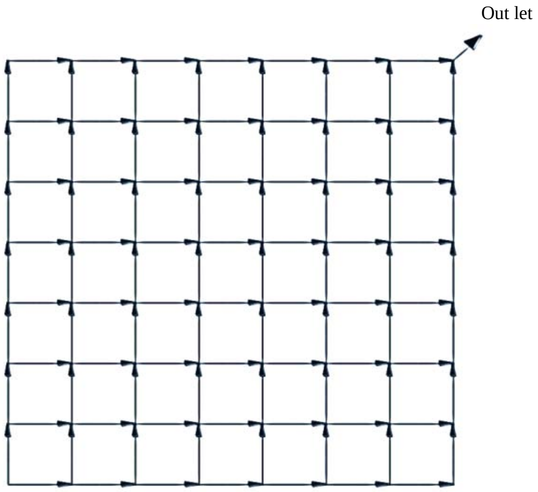

Fig. 1: Directed base graph Walters and Smith (1995)

Case study: A first sector from Al-Amil quarter in karbala city, Iraq was used exam the new proposed method. Karbala is located in the central region of Iraq. The city of Karbala was chosen for several reasons. There is no significant change in terrain heights and therefore, the designer cannot see the clear tracking of natural land slopes to the specific outlet. In such areas, there is often a lot of possible options for connecting sewers networks and the location of the network outlet. There is only one outlet discharging to sewage treatment plant. The design discharge is 250 L/ca/day. This value is provided by the sewer network which includes 216 nodes and 215 pipes, the total length of network (8.227 km). It forms about (0.485) and the layout of the present network shown in Fig. 3. When using the objective function to calculate the total cost of actual design for layout of network as build, a total cost was obtained equal 450.92 units. Table 1 presents the data characteristics as build for this network and information of actual layout design by manually.

Figure 4 shows the performance of the proposed GA-TGA model with the case study. The result was obtained with an Exponential Rank Selection (ERS) method was the best selection method worked with present model in previous benchmark example, Order crossover (OX), the probability of crossover Pc = 0.9, one-gene mutation per chromosome, the probability of mutation Pm = 0.5 and population size equal to

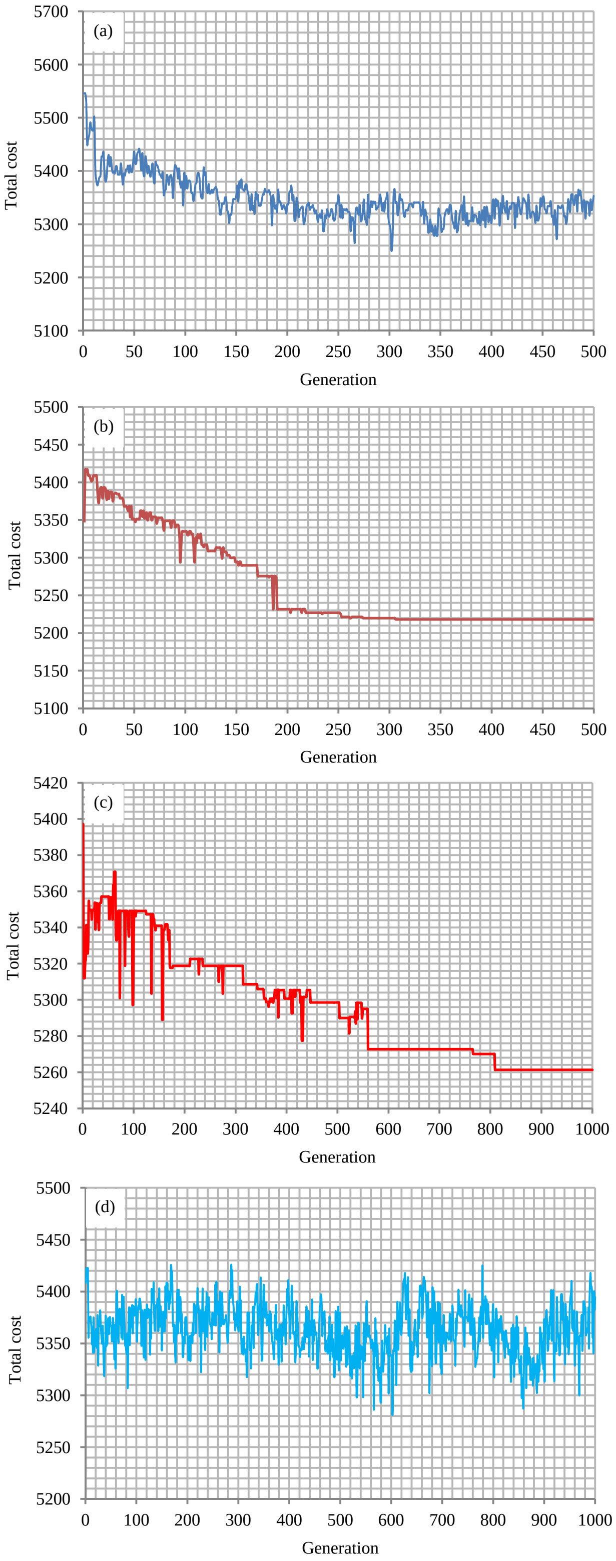

Fig. 2(a-d): Convergence characteristics of generations for different selection methods (a) RWS, (b) ERS, (c) SUS and (d) RMS, by the present model

Fig. 3: Existing layout of case study (first sector from Al-Amil district)

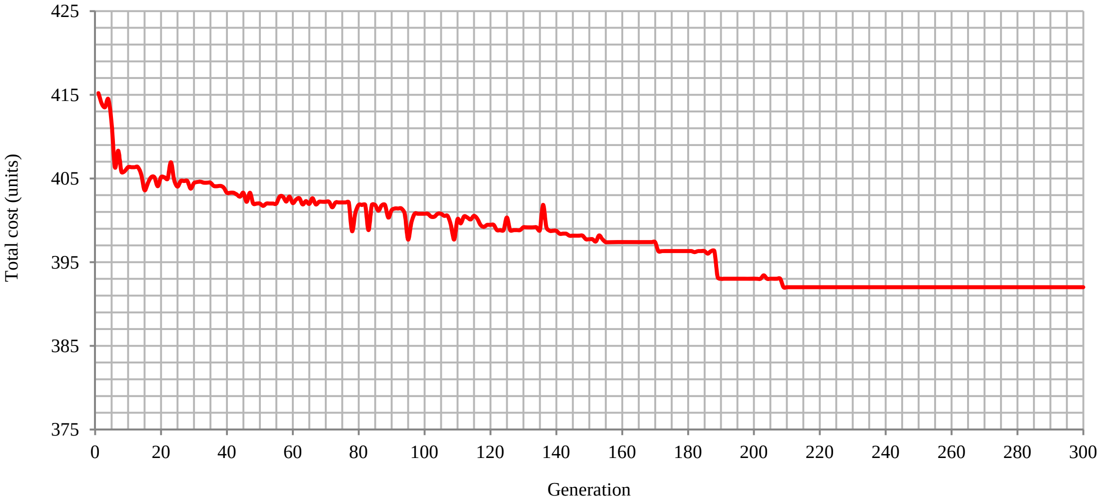

Fig. 4: Optimum cost solution by the proposed method for the case study

200 chromosomes. Repeatedly running the program, the optimum layout with minimum cost equal 392.0 units is gained in 209 generations as shown in Fig. 5, resulting in a reduction of about 13.05%, this reduction is relatively very good because of the initial cost of establishing sewerage networks, which are an important part of the city's infrastructure. Table 2 presents the data characteristics for optimum layout design of the case study by proposed model.

Fig. 5: Optimum layout of case study obtained by proposed model

Table 1: Existing layout design for the first case study

Link from	to	Length (m)	Q design ($m^3 sec^{-1}$)	Link from	to	Length (m)	Q design ($m^3 sec^{-1}$)
1	2	40	0.000355	103	107	30	0.014660
2	3	50	0.000790	104	105	40	0.000355
3	4	50	0.001224	105	106	45	0.000746
4	5	29	0.001474	106	107	45	0.001137
5	10	30	0.001735	107	110	56	0.016276
6	7	40	0.000355	108	109	40	0.000355
7	8	45	0.000746	109	110	40	0.000703
8	9	45	0.001137	110	348	30	0.017230
9	10	45	0.001527	112	113	50	0.000443
10	11	29	0.003506	113	115	50	0.000877
11	16	30	0.003766	114	115	45	0.000399
12	13	40	0.000355	115	116	50	0.001701
13	14	45	0.000746	116	347	50	0.002135
14	15	45	0.001137	119	120	40	0.000355
15	16	45	0.001527	120	121	40	0.000703
16	17	28	0.005528	121	122	35	0.001006
17	22	30	0.005789	122	345	35	0.001310
18	19	40	0.000355	125	126	40	0.000355
19	20	45	0.000746	126	127	40	0.000703
20	21	45	0.001137	127	128	35	0.001006
21	22	45	0.001527	128	343	35	0.001310
22	23	33	0.007595	131	132	40	0.000355
23	28	30	0.007855	132	133	40	0.000703
24	25	40	0.000355	133	134	35	0.001006
25	26	45	0.000746	134	341	35	0.001310
26	27	45	0.001137	137	138	40	0.000355
27	28	45	0.001527	138	139	40	0.002873
28	35	33	0.009660	139	140	40	0.003220
29	30	40	0.000355	140	141	40	0.003567
30	31	40	0.000703	141	142	40	0.003914
31	32	40	0.001050	142	143	40	0.004262
32	33	40	0.001397	143	144	40	0.004609
33	34	40	0.001744	144	145	40	0.004956
34	35	40	0.002091	145	146	40	0.005303
35	36	40	0.012091	146	147	40	0.005650
36	37	40	0.012439	147	148	40	0.005998
37	38	45	0.012830	148	149	40	0.006345
38	64	45	0.013220	149	339	35	0.006648
39	40	40	0.000355	157	158	40	0.000355

Table 1: Continue

Link from to		Length (m)	Q design (m^3 sec^{-1})	Link from to		Length (m)	Q design (m^3 sec^{-1})
40	41	40	0.000703	158	159	40	0.000703
41	42	40	0.001050	159	160	40	0.001050
42	43	40	0.001397	156	160	20	0.000181
43	44	40	0.001744	160	161	30	0.001483
44	45	40	0.002091	161	165	30	0.001744
45	56	40	0.002439	162	163	40	0.000355
46	47	40	0.000355	163	164	40	0.000703
47	48	35	0.000659	164	165	40	0.001050
48	50	35	0.000963	165	166	30	0.003046
49	50	40	0.000355	166	170	30	0.003306
50	51	32	0.001588	167	168	40	0.000355
51	55	30	0.001848	168	169	45	0.000746
52	53	40	0.000355	169	170	45	0.001137
53	54	35	0.000659	170	171	30	0.004695
54	55	35	0.000963	171	175	30	0.004955
55	56	50	0.003238	172	173	40	0.000355
56	57	30	0.005928	173	174	45	0.000746
57	62	30	0.006188	174	175	45	0.001137
58	59	40	0.000355	175	176	30	0.006344
59	60	40	0.000703	176	180	30	0.006605
60	61	40	0.001050	177	178	40	0.000355
61	62	40	0.001397	178	179	40	0.000703
62	63	28	0.007820	179	180	45	0.001093
63	64	30	0.008080	180	181	25	0.008124
64	65	32	0.021570	181	182	30	0.008384
65	70	35	0.021874	182	183	30	0.008645
66	67	40	0.000355	183	188	30	0.008905
67	68	45	0.000746	184	185	40	0.000355
68	69	45	0.001137	185	186	40	0.000703
69	70	45	0.001527	186	187	50	0.001137
70	71	31	0.023662	187	188	50	0.001571
72	73	40	0.000355	188	189	30	0.010728
73	74	40	0.000703	189	193	30	0.010988
74	76	40	0.001050	190	191	40	0.000355
75	76	40	0.000355	191	192	40	0.000703
76	77	32	0.003844	192	193	40	0.001050
77	81	30	0.004105	193	194	30	0.012291
78	79	40	0.000355	194	198	30	0.012551
79	80	40	0.000703	195	196	40	0.000355
80	81	40	0.001050	196	197	40	0.000703
81	81A	29	0.005398	197	198	40	0.001050
150	151	40	0.000355	198	209	56	0.014080
151	152	40	0.000703	199	200	40	0.000355
152	154	40	0.001050	200	201	45	0.000746
153	154	30	0.000268	201	202	45	0.001137
154	155	40	0.001657	202	206	55	0.001615
155	81A	20	0.001830	203	204	40	0.000355
81A	82	12	0.007324	204	205	45	0.000746
82	83	40	0.007673	205	206	45	0.001137
83	84	40	0.008020	206	207	40	0.003090
84	85	45	0.008411	207	208	45	0.003828
85	86	45	0.008802	208	209	45	0.004956
86	87	45	0.009192	209	210	20	0.019200
87	88	30	0.009452	210	211	38	0.019531
88	92	30	0.009712	211	212	45	0.019922
89	90	40	0.000355	212	213	45	0.020312
90	91	45	0.000746	213	338	45	0.020703
91	92	45	0.001137	338	339	25	0.020919
92	93	30	0.011101	339	340	30	0.027820
93	97	30	0.011362	340	341	29	0.028072
94	95	40	0.000355	341	342	30	0.029634
95	96	45	0.000746	342	343	30	0.029895
96	97	45	0.001137	343	344	30	0.031457
97	98	30	0.012751	344	345	30	0.031718
98	102	30	0.013011	345	346	30	0.035450
99	100	40	0.000355	346	347	30	0.035711
100	101	45	0.000746	347	348	30	0.038098
101	102	45	0.001137	348	349	30	0.055320
102	103	30	0.014400		8227		

Table 2: Optimum layout design for the case study by proposed model

Pipe from to		Length (m)	Q design (m^3 sec^{-1})	Pipe from to		Length (m)	Q design (m^3 sec^{-1})
1	2	40	0.000355	100	101	45	0.000746
2	3	50	0.000790	101	102	45	0.001137
3	4	50	0.001224	102	103	30	0.014400
4	5	29	0.001474	103	107	30	0.014660
5	10	30	0.001735	104	105	40	0.000355
6	7	40	0.000355	105	106	45	0.000746
7	8	45	0.000746	106	107	45	0.001137
8	9	45	0.001137	107	110	56	0.016276
9	10	45	0.001527	108	109	40	0.000355
10	11	29	0.003506	109	110	40	0.000703
11	16	30	0.003766	110	348	30	0.017230
12	13	40	0.000355	112	113	50	0.000443
13	14	45	0.000746	113	115	50	0.000877
14	15	45	0.001137	115	116	50	0.025299
15	16	45	0.001527	116	347	50	0.025734
16	17	28	0.005528	119	120	40	0.000355
17	22	30	0.005789	120	121	40	0.000703
18	19	40	0.000355	121	122	35	0.001006
19	20	45	0.000746	122	345	35	0.001310
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27	28	45	0.001527	134	341	35	0.001310
28	35	33	0.009660	137	138	40	0.000355
29	30	40	0.000355	138	139	40	0.002873
30	31	40	0.000703	139	140	40	0.003220
31	32	40	0.001050	145	144	45	0.000399
32	33	40	0.001397	144	143	40	0.000746
33	34	40	0.001744	143	142	40	0.001093
34	35	40	0.002091	142	141	40	0.001440
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36	37	40	0.012439	140	115	55	0.023998
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56	57	30	0.005928	171	175	30	0.004955
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63	64	30	0.008080	178	179	40	0.000703
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65	70	35	0.021874	180	181	25	0.008124
66	67	40	0.000355	181	182	30	0.008384
67	68	45	0.000746	183	182	30	0.009886

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70	71	31	0.023662	185	186	40	0.003845
72	73	40	0.000355	186	187	50	0.004280
73	74	40	0.000703	187	188	50	0.004714
74	76	40	0.001050	189	188	30	0.004660
75	76	40	0.000355	193	189	30	0.004400
76	77	32	0.003844	190	191	40	0.000355
77	81	30	0.004105	191	192	40	0.000703
78	79	40	0.000355	192	193	40	0.001050
79	80	40	0.000703	194	193	30	0.003098
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155	81A	20	0.001830	201	200	45	0.000790
81A	82	12	0.007324	200	199	40	0.001137
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84	85	45	0.008411	205	204	45	0.000790
85	86	45	0.008802	204	203	40	0.001137
86	87	45	0.009192	203	185	46	0.001536
87	88	30	0.009452	206A	207	30	0.000268
88	92	30	0.009712	207	208	45	0.000659
89	90	40	0.000355	208	209	45	0.001050
90	91	45	0.000746	339	340	30	0.001570
91	92	45	0.001137	340	341	29	0.001822
92	93	30	0.011101	341	342	30	0.003384
93	97	30	0.011362	342	343	30	0.003645
94	95	40	0.000355	343	344	30	0.005207
95	96	45	0.000746	344	345	30	0.005468
96	97	45	0.001137	345	346	30	0.009200
97	98	30	0.012751	346	347	30	0.009461
98	102	30	0.013011	347	348	30	0.035446
99	100	40	0.000355	348	349	30	0.052668

CONCLUSION

The adaptive Genetic Algorithm procedure have been successfully developed-in a hybrid optimization model which combines GAs with a TGA to enable optimal tree networks to be selected from directed base graphs of sewer network. The drawbacks of using this approach are few and the benefits are such that optimization runs can either be made shorter to achieve a given goal or discover better results in a fixed timeframe. These algorithms require only limited computer facilities and can be used to design the layout of large nonlinear flow networks.

Comparison of the solution for the benchmark example obtained by proposed model with reduction in search space, with the solutions provided by Walters and Smith, 1995, indicated that the modified model is more efficient and effective in finding similar result (5218 units) with much reduced computational effort. As well as the lack of the need to repair or discard infeasible layouts or even apply the factors of penalty on the cost function. This improves the performance of the optimization model more efficiently in terms of speed and accuracy.

In order to ensure the efficiency of the proposed method for the design of real networks, it was examined with case study located in Karbala Holy city, Iraq, then compared the cost of the manual designs with the designs obtained from this model for networks. The saving percentage was 13.05%, the savings percentage obtained through the optimal design by using the proposed GA-TGA model indicate that the model is well performing.

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