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Optimal design of municipal wastewater collection networks with long-term performance improvement approach

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NSGA-II;
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Hydraulic performance.

Abstract. The purpose of this study is to achieve an optimal performance-based design of municipal wastewater collection networks. Sewer deterioration decreases system performance over time and investigations have shown that diameter, slope, structural condition, length, and burial depth are effective factors in hydraulic and structural deterioration. In this research, these factors were used first to develop performance indicators based on velocity, depth of flow, burial depth, pipe slope, and pipe length. Then, using the Non-dominated Sorting Genetic Algorithm II (NSGA-II) and pipe diameter as decision variable, the optimal design of a case study was performed under different combinations of performance indicators. Part of Kerman's wastewater collection network that includes 20 manholes and 20 pipes and one outlet is considered as a case study. The results showed that the pareto points in different combinations of factors influencing the overall performance are very similar and in all scenarios, the designs tend to increase the slope of the pipe, decrease the diameter, and increase the depth of burial. It was observed that the performance of the network could be improved by about 2% in the case study and almost without imposing additional costs on the basic design.

1. Introduction

Wastewater collection networks, in addition to the high initial investment, have significant maintenance and operational costs. Therefore, optimizing the performance and reducing the costs of network operation and maintenance are very important. Optimal design of wastewater collection networks with optimum service that can transfer wastewater without imposing additional hydraulic load on the system increases the performance and reduces the maintenance costs during operation. Thus, the performance-based optimal design should be taken into account.

Optimal design of wastewater collection networks has been performed in three areas: network's dimensions optimization (pipes diameter), network layout optimization, and simultaneous optimization of layout and network dimensions. Dimension optimization with different algorithms and decision variables has been investigated by some researchers [1–8]. For simultaneous optimization of layout and network dimensions, the following researches can be mentioned [9–11]. From the literature, optimization was applied only to minimize the construction costs of wastewater collection network.

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Performance of wastewater collection networks is defined as the ability of its service to people in the area concerned over the useful life of the network and under various daily conditions. The hydraulic performance of wastewater collection networks cannot be directly evaluated because it does not have a precise mathematical relationship. Therefore, to evaluate the hydraulic performance of these networks, one must consider the hydraulic, mechanical, and qualitative properties such as velocity, depth of flow, etc., which can be directly measured [12].

Cardoso et al. [13] used a number of performance indicators to evaluate the impact of infiltration and inflow in separate and combined sewer networks in Assessing infiltration and exfiltration on the Performance of Urban Sewer Systems (APUSS) project. It was one of the first efforts to evaluate the performance of combined municipal sewer networks. For this purpose, two penalty curves for velocity and surface area of the sewer within the sewer were used. Performance scoring began with zero (failure mode) and ended with 4 (optimal service mode).

Tabesh and Madani [12] determined the hydraulic performance of sewer networks with two penalty curves for velocity and depth of flow based on the standard codes and research conducted in the field of sewer networks. In this method, the performance scoring varied from zero (failure service mode) to 1 (optimal service mode) with 0.25 steps.

Akhondian and Tabesh [14] optimized the design of wastewater collection networks using the reliability constraint as a probable combination of hydraulic performance indicator based on the depth of flow developed by Tabesh and Madani [12]. In fact, the increase of hydraulic load was considered as reliability and a relation based on hydraulic performance indicator (depth of flow) at different design flow ratios was developed.

Heydarzadeh et al. [15] developed a new model for the multi-objective design of sewer network with the aim of increasing the efficiency of wastewater treatment within the sewers. In the developed model, hydraulic and qualitative parameters of sewage flow inside the sewers were considered. Results showed that raising the removal of organic matter within the sewer could be achieved, but the values of other performance indices might worsen.

So far, the effects of structural conditions on the hydraulic and overall performance and parameters affecting the performance have received less attention in the literature. Water Research Center (WRC) [16] investigated the factors affecting sewer deterioration as system performance deteriorating factors over time. It divided the process of sewer deterioration into two categories: structural deterioration and hydraulic deterioration. Structural deterioration is characterized by structural defects such as cracks and can cause structural failure. Hydraulic deterioration is characterized by hydraulic defects such as sediment and sedimentation and can reduce transmission capacity and ultimately cause hydraulic failure [17,18]. Also, structural deterioration directly affects the hydraulic capacity and hydraulic deterioration of sewers and can cause disruption of sewers transmission capacity [19].

Numerous potential factors cause sewer deterioration. Several studies have shown that each of these factors can lead to structural and hydraulic deterioration, or both types [18]. In addition, it has been observed that pipes with different materials and characteristics have different deterioration behaviors. Thus, deterioration factors are considered as variables in the development and calibration of deterioration models. Understanding the most important factors among all deterioration factors is key to studying the deterioration process of a sewer network for the following reasons [18]:

1. Reducing the number of variables needed to calibrate deterioration models considering the high costs of data collection. In this respect, acceptable accuracy can be obtained with fewer variables if the relationship between the factors is specified;
2. By increasing the reliability of proper prediction of deterioration models, quality forecasts can only be obtained if information on the most important factors is available.

According to various related studies, the factors of construction and operation year, material, cross-sectional dimensions (diameter), cross-sectional shape, depth, length, slope, bed soil, method of implementation, quality of network management, sewage type, sewer maintenance, traffic load, groundwater level, tree presence, soil type, and proximity to other facilities have been identified as effective structural deterioration factors [18–24]. Diameter, slope, presence of trees, groundwater, and structural conditions have also been identified as factors affecting the hydraulic deterioration of sewers [18,19,25].

In summarizing the studies on network deterioration, the following parameters are selected: cross-sectional dimensions (diameter), slope, length and burial depth as important factors affecting structural deterioration and cross-sectional dimensions (diameter), slope, and structural conditions of sewers as important factors affecting hydraulic deterioration. In this research, all the above-mentioned parameters are taken into account in defining new performance indices. Then, a method for determining the performance-based multi-objective optimal design of sewer networks is developed. The following describes the hydraulic modeling of wastewater collection networks, the assumptions used, design criteria, and the network hydraulic design algorithm.

2. Material and methods

Since the sewers normally act as an open channel, the following assumptions are considered for hydraulic modeling:

- The wastewater flow is steady and uniform;
- Velocity distribution at the cross-section is constant and equal to the average velocity;
- Wastewater is an incompressible material.

Flow in sewer pipes generally obeys the Manning equation and can be analyzed using Eq. (1):

$$Q = \frac{1}{n} A R^{2/3} S^{1/2}, \tag{1}$$

where Q is the pipe discharge rate (m^3/s), n the Manning roughness coefficient, A the cross-sectional area of the flow (m^2), R: the hydraulic radius (m), and S the channel slope. The sewer cross-section is circular. Design constraints include velocity limits, allowable slope, sewer dimensions, burial depth, depth of flow, and progressive diameters which are reflected in Eqs. (2) to (7), respectively:

$$V_{\min} \le V_i \le V_{\max}, \tag{2}$$

$$S_{\min} \le S_i \le S_{\max}, \tag{3}$$

$$D_i \ge D_{\min}, \tag{4}$$

$$HD_{\min} \le X_i \le HD_{\max}, \tag{5}$$

$$\left(\frac{h}{D}\right)_i \le \left(\frac{h}{D}\right)_{\max}, \tag{6}$$

$$D_{up} \ge D_{down}, \tag{7}$$

where $V_i, V_{\min}$, and $V_{\max}$ denote the velocity of pipe i (m/s) and minimum and maximum allowable velocities (m/s), respectively. $S_i, S_{\min}$, and $S_{\max}$ denote the slope of pipe i and minimum and maximum allowable slopes, respectively. D_i and $D_{\min}$ denote the diameter of pipe i (m) and minimum allowable diameter (m), respectively. $X_i, HD_{\min}$, and $HD_{\max}$ denote the average depth of pipe i (m) and minimum and maximum allowable covers (m). $\left(\frac{h}{D}\right)_i$ and $\left(\frac{h}{D}\right)_{\max}$ denote the flow depth to the pipe diameter of pipe i and its maximum value, respectively. Finally, D_{up} and D_{down} denote the upstream and downstream sewer diameters (m), respectively.

Eq. (8) shows the proposed objective function to estimate the costs of the sewer network [25]:

$$Minimaize\ C_T = \sum_{i=1}^{N} \left(C_{pi} \times L_i + C_{mi} + C_{psi}\right), \tag{8}$$

where N is the number of pipes, L_i the length of the pipe i, C_{pi} the cost per unit length of the pipe i, C_{mi} the construction cost of manhole i, and C_{psi} the cost of the pumping station in manhole i. C_{Pi} is a function of the pipe diameter and the average pipe burial depth. In this study, the diameter of the pipes is considered as the decision variable.

The costs of implementing the wastewater collection network are presented in the form of Eqs. (9) and (10) [25]:

$$C_{pi} = 1.93 e^{3.43 D_i} + 0.812 {d_i}^{1.53} + 0.437 {d_i}^{1.47} D_i, \tag{9}$$

$$C_{mi} = 41.46 E_{mi}, \tag{10}$$

where e is the Napier's constant, D_i the diameter of pipe i (m), d_i he average excavation depth in pipe i (m), and E_{mi} the height of the manhole in the upstream of pipe i (m). Construction cost of manhole is three times the cost of one meter of pipe with a diameter of one meter and all cost coefficients are calculated by regression of actual values [25].

2.1. Hydraulic modeling algorithm

Manning equation has been used for hydraulic modeling of sewer network. By specifying the network diameters, the algorithm begins to find the best slopes to satisfy all constraints. Part of the final proposed algorithm for designing wastewater collection networks is its hydraulic modeling, which required the following explanations:

1. Input information: Including minimum and maximum design constraints and network specifications such as pipe number, upstream and downstream number of each pipeline, upstream and downstream manholes, length of sewers, the design flow of each sewer, and the diameter of the sewers;
2. Identifying branch and middle sewers: Branch sewer has no inlet on the upstream manhole and middle sewer has at least one inlet in its upstream manhole;
3. Calculating $S_{\min}$ and $S_{\max}$ of sewers: Besides a value proposed by the standard codes, two other values are obtained for the minimum slope using the manning equation considering the two cases of $V_{\min}$ and $\left(\frac{h}{D}\right)_{\max}$ with the highest value is selected. To calculate $S_{\max}$, only the constraint of $V \le V_{\max}$ is used according to the standard codes. Figure 1 explains the proposed design algorithm.

2.2. Performance indicators

To determine the hydraulic performance of wastewater collection networks, Tabesh and Madani [12] developed two penalty curves for velocity and depth of flow using design regulations and related standards. The horizontal axis of these curves is based on the studied parameters. The performance indicator shown on the vertical axis is divided into four sections from zero

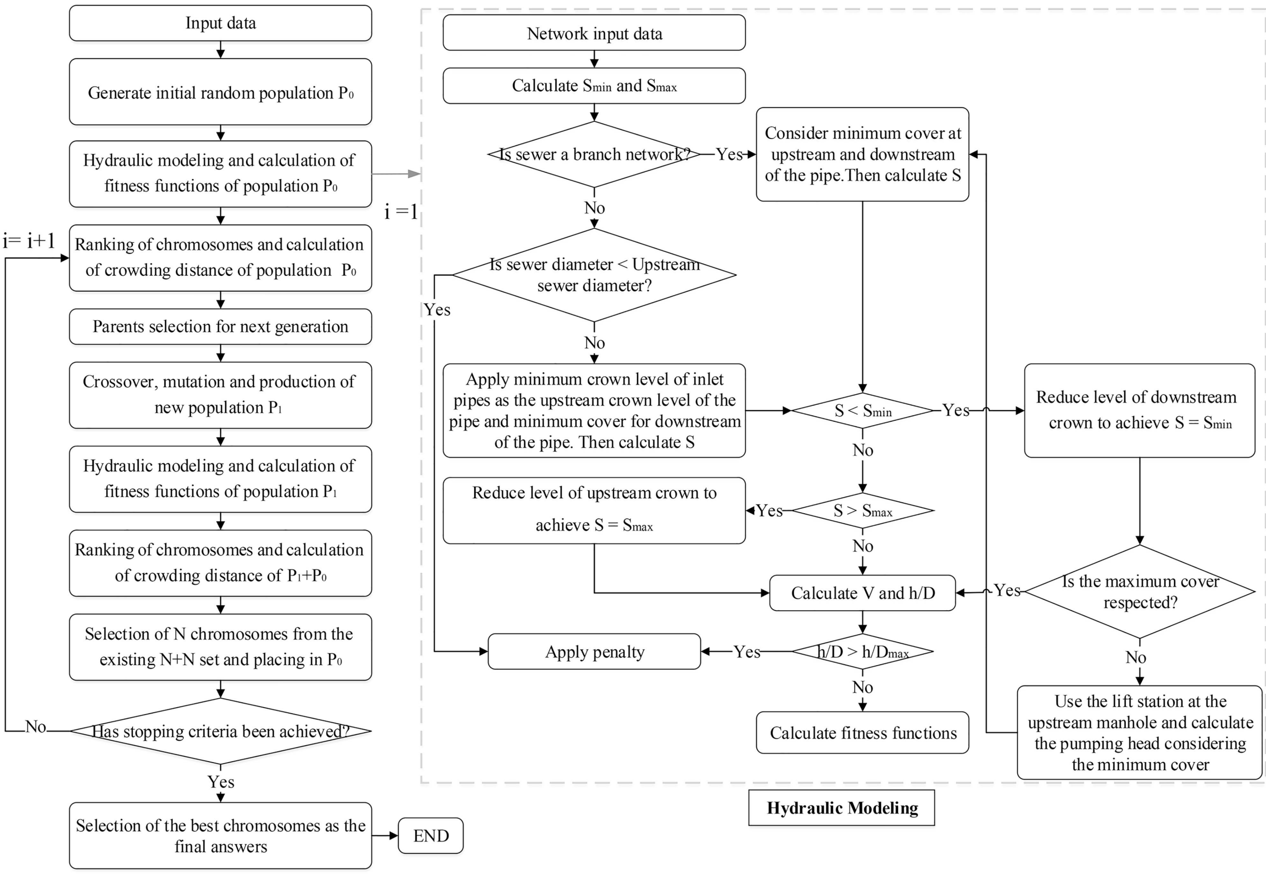

Figure 1. Flowchart of the proposed design algorithm (the hydraulic analysis and the NSGA-II optimization models).

to one with 0.25 increments. Zero means no service, which is totally unacceptable. 0.25 is related to the unsatisfactory level of service. 0.5 means minimum acceptable level of service. 0.75 indicates acceptable level of service and 1 illustrates excellent performance. In this study, 5 penalty curves for velocity, depth of flow, burial depth, and sewer length are developed to quantify the condition of the sewer network.

2.2.1. Penalty curves for pipe velocity

Sewers with very low slopes are more likely to form hydrogen sulfide gas due to low velocity of wastewater flow, which will cause corrosion and odor problems in long time. High-slope sewers will have a higher deterioration rate due to increased corrosion from high velocities. According to a study of sewers with different slopes, slopes less than 1% and more than 5% had the highest structural deterioration rates [20].

Based on design rules, the minimum allowed velocity is equal to the self-cleaning velocity, which must be provided so that problems related to sedimentation do not occur. This velocity is equal to 0.7, 0.8, and 0.9 m/s for diameters smaller than or equal to 300 mm, smaller than or equal to 600 mm, and greater than 600 mm, respectively [26]. The maximum velocity limit is 4.5 m/s. In the case of maximum velocity, in special cases, the maximum velocity in separate networks can be increased up to 6 m/s. Figure 2 is drawn considering the velocity of 1.2 to 3 m/s as the optimal service thresholds [26].

2.2.2. Penalty curves for depth of flow

Hydraulic defects are mainly due to the insufficient sewer capacity and its unsuitable slope. Improper design increases the risk of sedimentation and blockage [19]. According to Figure 3, $h/D = 0.1$ is considered as an unacceptable service threshold. As the h/D increases from 0.1 to 0.5, the performance of the wastewater collection network increases [12].

Optimal hydraulic performance for sewers occurs at $0.5 < h/D < 0.65$ for diameters smaller than 400 mm and $0.5 < h/D < 0.75$ for other diameters. Also, according to the hydraulic rules of flow, if $h/D > 0.80$, then the instability of the flow and the change of normal depth will occur, whilst the maximum velocity for this ratio occurs [12]. Therefore, $h/D = 0.80$ is considered as an acceptable design threshold. The highest capacity of flow transition occurs at $h/D = 0.80$, at which the aeration of the sewage is difficult. Therefore, at ratios larger than the mentioned value, the value of the performance indicator will be zero.

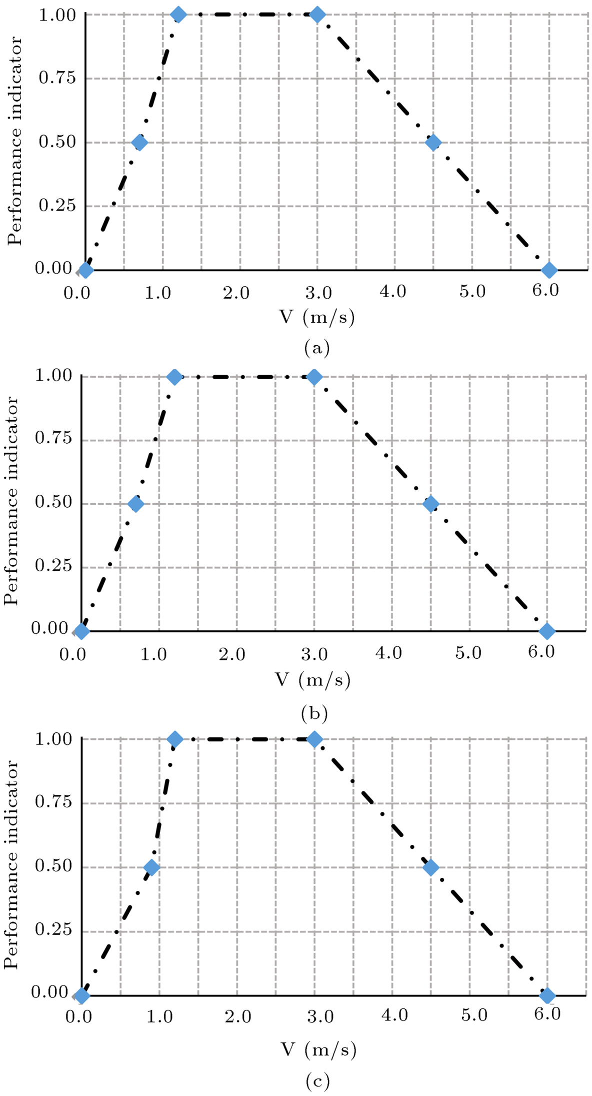

Figure 2. Velocity penalty curves for diameters of: (a) smaller than or equal to 300 mm, (b) smaller than or equal to 600 mm, and (c) greater than 600 mm.

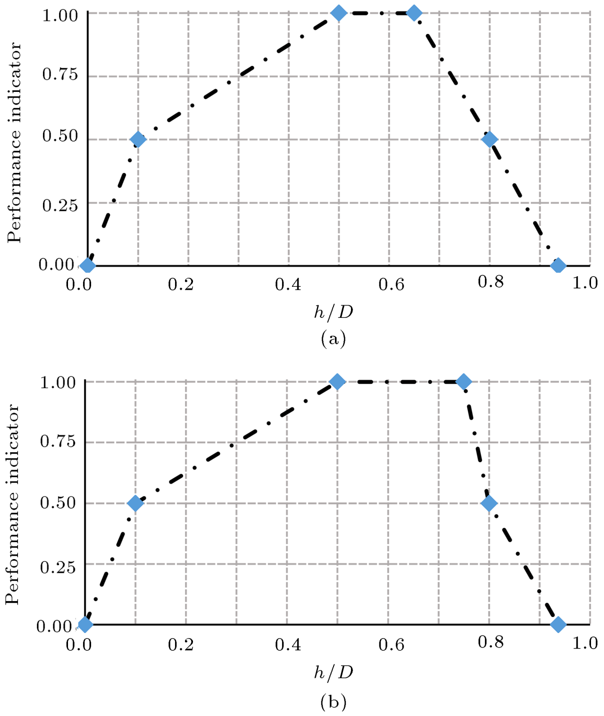

Figure 3. Penalty curves for depth of flow at diameters: (a) smaller than 400 mm and, (b) equal to or larger than 400 mm.

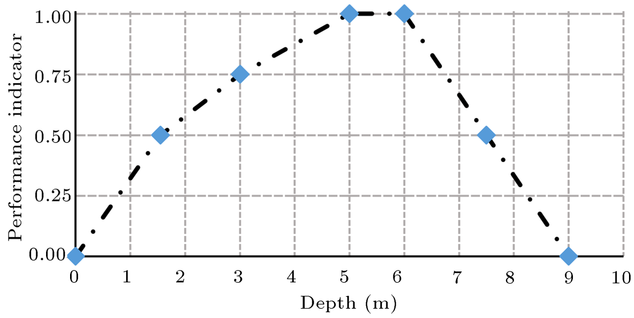

Figure 4. Penalty curve for the burial depth.

2.2.3. Penalty curve for burial depth

Numerous factors, including traffic, soil moisture, frost, and soil load on the sewers can cause structural defects for sewers. For burial depth less than 2 and more than 5.5 m, 'traffic load and the impact of environmental factors' and 'increased soil pressure', respectively, have the greatest impact on structural deterioration [21,23].

In Figure 4, burial depths of 1.2+D m (D: sewer diameter) and 7.5 m are considered as the minimum acceptable levels of service thresholds. Out of this range, acceptable performance will not be provided. Burial depth of 3 m with a performance indicator of 0.75 is in an acceptable level of service; and between burial depths of 5 and 6 m, excellent service will be provided [26,27].

2.2.4. Penalty curve for sewer length

Sewers with larger length are more prone to damage because one of the main causes of damage and deterioration of sewers is the joints whose number increases in the longer pipes. They are also exposed to greater bending stresses [19,25].

According to the diameter and operation equipment, the distance between manholes on direct routes is as follows [26]:

- For pipes with a diameter of 500 mm and less: 90–120 m;
- For pipes with a diameter of 600 mm and more: 120–150 m.

Figure 5 shows the penalty curves of the sewer length.

2.2.5. Penalty curve for sewer slope

Slope changes directly affect the flow velocity; thus, the slope effect is taken into account by controlling the

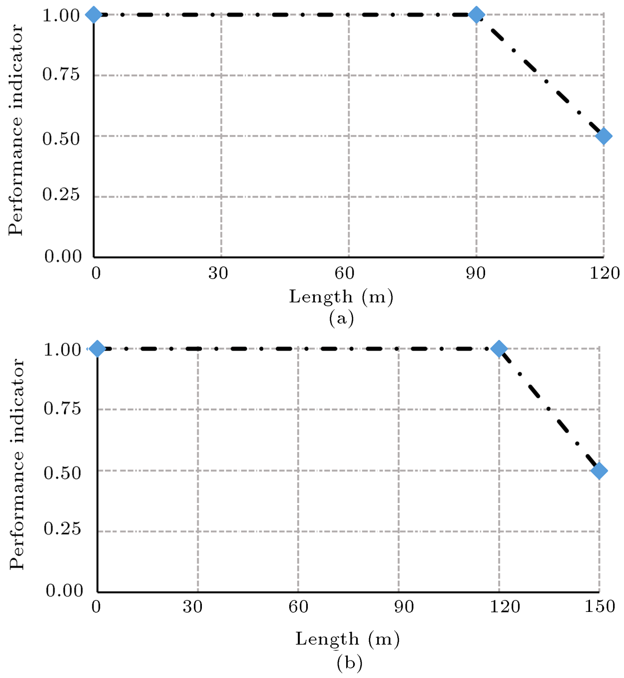

Figure 5. Sewer length penalty curves for diameters of: (a) smaller than or equal to 500 mm and (b) equal or larger than 600 mm.

velocity. For this purpose, penalty curves for sewer velocity have been used to apply the slope effect.

2.2.6. Network Performance Index (PI)

Eqs. (11) and (12) are used to determine the overall performance indices of velocity and depth of flow, respectively [12]:

$$PI_V = \frac{\sum_{i=1}^{N} (PI_{(V)_i} \times A_i \times L_i)}{\sum_{i=1}^{N} (A_i \times L_i)}, \tag{11}$$

$$PI_{\frac{h}{D}} = \frac{\sum_{i=1}^{N} (PI_{(\frac{h}{D})_i} \times A_i \times L_i)}{\sum_{i=1}^{N} (A_i \times L_i)}. \tag{12}$$

Similarly, for burial depth, length, and slope of sewers, Eqs. (13) to (15) have been developed in this paper:

$$PI_{Depth} = \frac{\sum_{i=1}^{N} (PI_{(Depth)_i} \times A_i \times L_i)}{\sum_{i=1}^{N} (A_i \times L_i)}, \tag{13}$$

$$PI_{Length} = \frac{\sum_{i=1}^{N} (PI_{(L)_i} \times A_i \times L_i)}{\sum_{i=1}^{N} (A_i \times L_i)}, \tag{14}$$

$$PI_{Slope} = \frac{\sum_{i=1}^{N} (PI_{(V)_i} \times A_i \times L_i)}{\sum_{i=1}^{N} (A_i \times L_i)}, \tag{15}$$

where L_i is the length of the sewer i (m), A_i the cross-sectional area of the sewer i (m^2), and N the number of pipes. $PI_{(V)}$, $PI_{(\frac{h}{D})_i}$, $PI_{(Depth)_i}$, and $PI_{(L)_i}$ are performance indicators of velocity, depth of flow, burial depth, and length of sewer i, respectively. PI_V, $PI_{\frac{h}{D}}$, PI_{Depth}, PI_{Length}, and PI_{Slope} are network performance indices of velocity, depth of flow, burial depth, length, and slope, respectively. To achieve each of the structural and hydraulic performance indices, the numbers obtained for the performance indicators are combined with the weighted average geometric method. Eqs. (16) to (18) explain how to calculate the structural, hydraulic, and the overall performance indices of the system, respectively.

$$PI_S = \left(\sum_{i=1}^{k} PI_i^{\,e_i}\right)^{1/\sum_{i=1}^{k} e_i}, \tag{16}$$

$$PI_H = \left(\sum_{j=1}^{m} PI_j^{\,f_j}\right)^{1/\sum_{j=1}^{m} f_j}, \tag{17}$$

$$PI = (PI_S^{\,w_1} \times PI_H^{\,w_2})^{1/(w_1+w_2)}, \tag{18}$$

where e_i and f_i are significance factors of the present indicators in structural and hydraulic indices, respectively. k and m are the number of present indicators in structural and hydraulic performances, respectively. w_1 and w_2 indicate the weight of structural PI and the weight of hydraulic PI of the sewer network, respectively. PI_S, PI_H, and PI are structural, hydraulic, and overall performance indices, respectively.

3. Results

Evaluation of the method presented in this study is based on a part of Kerman's wastewater collection network, which has been selected as a case study. This network was first solved by Mansouri and Khanjani [25] using constrained programming and a hydraulic model based on the Manning equation with constant roughness and modified Hazen-Williams. Figure 6 shows the schematic of this simple network that includes 20 manholes, 20 pipes, and one outlet. Network information is given in Table 1.

The assumptions and limitations used to solve this problem are as follows:

- Manning roughness coefficient (n) = 0.013 (constant);
- Minimum and maximum velocities ($V_{\min}$ and $V_{\max}$) = 0.3 and 3 m/s, respectively;
- Minimum cover = 2.45 m;
- $(h/D)_{\max} = 0.82$;
- Population size = 100, generation number = 240, crossover rate = 0.8, and mutation rate = 0.01 on 20% of the population.

The standard diameters considered in this problem and the equivalent coding value are given in Table 2. It should be noted that in the reference of the

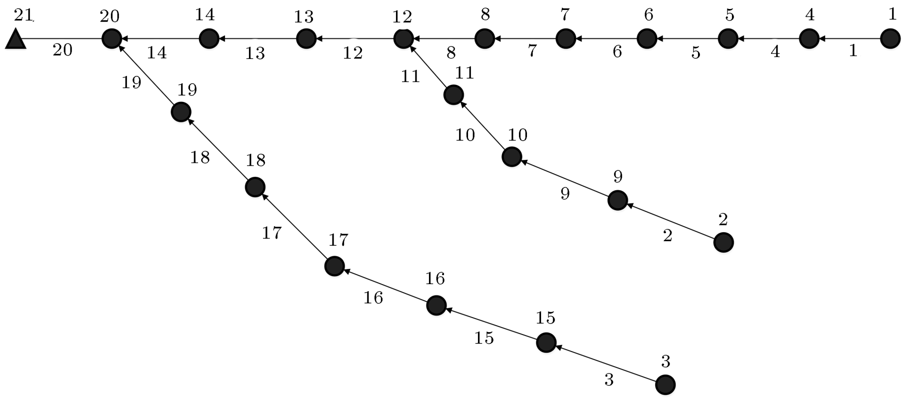

Figure 6. Layout of the studied network in Kerman city (Mansouri and Khanjani [25]).

Table 1. Information of sample network in a part of Kerman city (Mansouri and Khanjani [25]).

	Manhole no.			**Ground elev.**		
Pipe no.	**Upstream**	**Downstream**	**Length (m)**	**Upstream**	**Downstream**	**Flow (Lps)**
1	1	4	260	74.59	73.66	27.9
2	2	9	300	70.7	69.9	54.9
3	3	15	400	73	71.5	21.1
4	4	5	460	73.66	72.1	30.4
5	5	6	260	72.1	71.19	32.4
6	6	7	300	71.19	69.85	34
7	7	8	450	69.85	68.24	36.6
8	8	12	400	68.24	67.28	38.7
9	9	10	270	69.9	69.3	56.2
10	10	11	310	69.3	68.4	58
11	11	12	440	68.4	67.28	59.6
12	12	13	470	67.28	66.22	96.7
13	13	14	350	66.22	65.82	101.2
14	14	20	340	65.82	65.42	104.7
15	15	16	400	71.5	70.1	26.4
16	16	17	400	70.1	68.6	30
17	17	18	500	68.6	66.8	31.9
18	18	19	400	66.8	66.1	40.3
19	19	20	590	66.1	65.42	44.6
20	20	21	320	65.42	64.5	165.9

Table 2. The actual and coded values of the allowable sewer diameters.

Diameter (m)	**Binary gray code**	**Diameter (m)**	**Binary gray code**
0.2	0000	0.5	1100
0.225	0001	0.56	1101
0.25	0011	0.6	1111
0.28	0010	0.7	1110
0.3	0110	0.8	1010
0.35	0111	0.9	1011
0.4	0101	1	1001
0.45	0100	1.2	1000

Table 3. Comparison of the results of different studies in the base scenario.

Model	Method	Cost (Manning eq.)
Mansouri and Khanjani [25]	NLP	83,116
Afshar et al. [4]	CA	80,879
Afshar and Rohani [6]	Discrete HCA	77,327
Afshar et al. [28]	Adaptive CA (NORS)	77,285
Zaheri et al. [29]	Two-Phase CA	76,750
Hassan and Jassem [30]	GA-HP	81,265
Design with commercial software SewerGems V8i	82,932	
Present study	GA	80,964

Table 4. Multi-objective optimization design scenarios.

Scenario	Second objective function	Description
1	Hydraulic performance (velocity and depth of flow)	–
2	Structural performance (burial depth, pipe slope, and pipe length)	–
3	Hydraulic performance (velocity, depth of flow, and structural (burial depth, pipe slope, and pipe length))	The structural factor (burial depth, pipe slope, and pipe length) is considered as an effective factor in hydraulic performance.
4	Overall performance (hydraulic: velocity and depth of flow; and structural: burial depth, pipe slope and pipe length)	–
5	Overall performance (hydraulic: velocity, depth of flow and structural; and structural: burial depth, pipe slope and pipe length)	The structural factor (burial depth, pipe slope and pipe length) has been applied both independently and effectively in hydraulic performance.

first sample problem, information about the maximum cover was not mentioned. The results of this algorithm comparing the results of other researches in the base scenario are given in Table 3.

Comparison of the cost obtained from the single-objective model of the present study with other results shows that the model approached the answer with appropriate accuracy and can be a good base for development and achievement of the set goals. The reason for the difference is the accuracy of the calculations and simplifications performed and the design diameters set. Different researchers have considered different sets for diameters. In the multi-objective optimal design, 5 scenarios are defined and shown in Table 4. In all scenarios, the significance factors (e_i and f_i) of the indicators are considered equal to 1. Also, in all the scenarios, the values of the coefficients w_1 and w_2 are assumed to be 1.

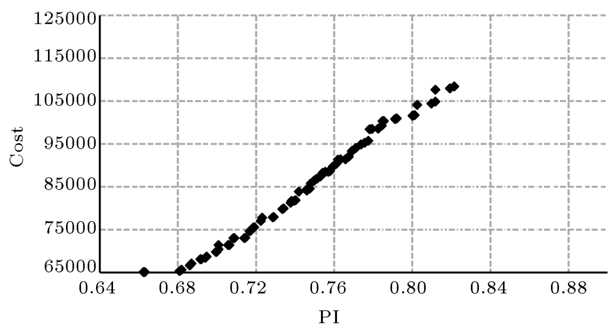

Figure 7. Pareto front of the multi-objective optimal design (scenario 1).

The first scenario in this study is hydraulic performance due to two factors: velocity and depth. The pareto front of this scenario is shown in Figure 7. In this figure, PI starts at 0.66 and continues until 0.82.

Figure 8(a)–(d) illustrate the results of scenar-

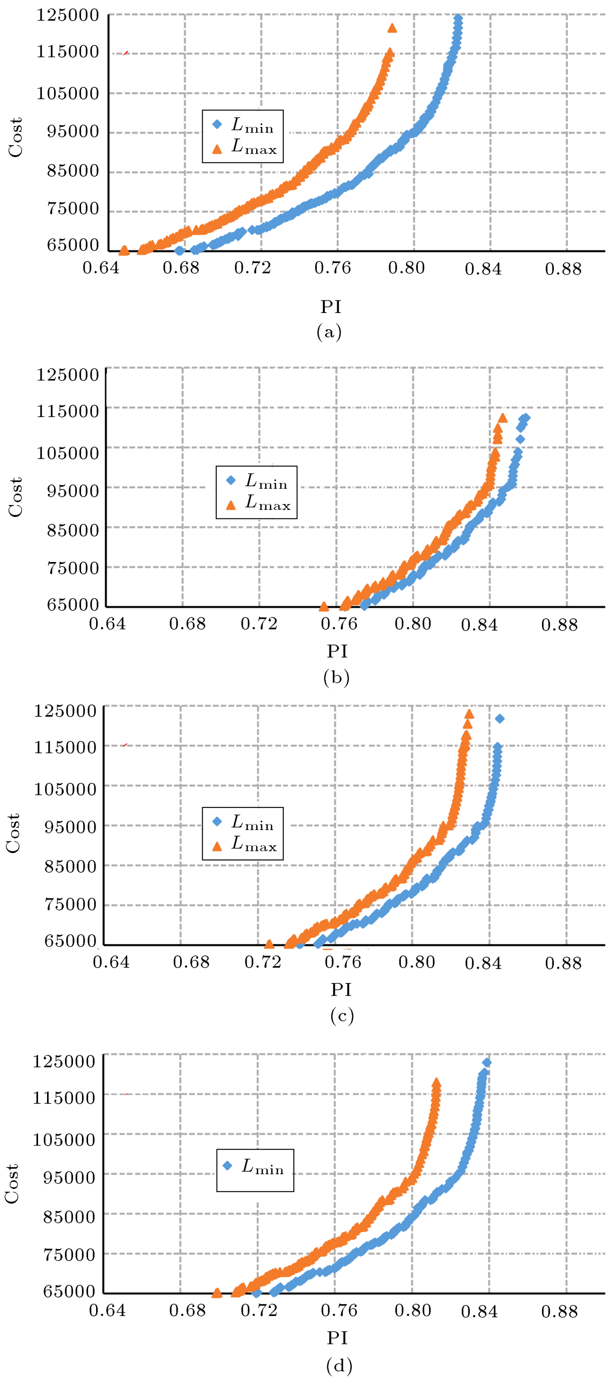

Figure 8. Pareto front of the multi-objective optimal design: (a) scenario 2, (b) scenario 3, (c) scenario 4, and (d) scenario 5.

ios 2–5, respectively. $L_{\min}$ means that the distance between two manholes follows the minimum allowable values; thus, the number of manholes increases. $L_{\max}$ means that the distance between two manholes follows the maximum allowable values. The difference in cost due to the number of manholes in these two statues is very small (about 0.5% of the total cost), which has been ignored.

According to this figure, the range of changes in network performance in Figure 8(a) starts at 0.65 and continues until about 0.82. In Figure 8(b), the performance changes are in the range of 0.75 to 0.86; in Figure 8(c), the performance changes are in the range of 0.73 to 0.85; and in Figure 8(d), the performance changes are in the range of 0.7 to 0.84. In the latest scenario, which is in fact the most comprehensive scenario defined in this study, the mode of change of average coverage with performance follows an upward trend and starts from 1.5 m and reaches 4.23 m at the end of the route. The slope of the graph is linear at the beginning of the path; however, from $PI = 0.82$ onwards, the slope of the changes is more than linear.

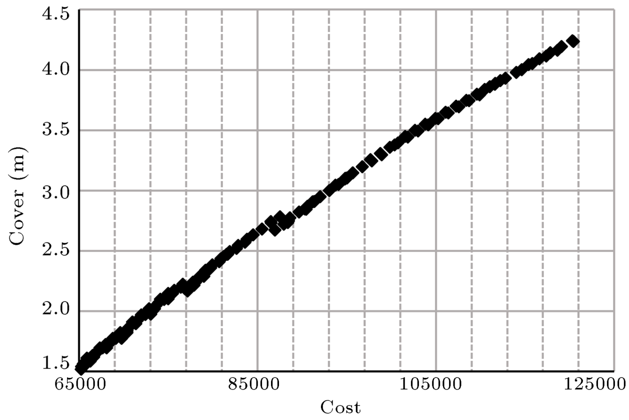

Figure 9. Cost trend versus the average burial depth in scenario 5 ($L_{\min}$).

Comparison of the scenarios suggests that with the development of the concept of performance and the consideration of various factors within the definition provided for it, the range changes slightly. Also, with the expansion of the definition and the consideration of various factors, the effects of different factors merge and each of the parameters alone cannot have much effect on the performance variation. This is consistent with the nature of collection networks.

The trend of cost changes in terms of average cover is shown in Figure 9. It is observed that the points have an upward trend and start from the cost of 65,066 with an average cover of 1.5 m; finally, they reach the highest performance and the highest amount of network cover (4.23 m) at a cost of 120,043.

4. Discussion

The results of this study were obtained by multiobjective optimization and it is not possible to achieve these results in a single-objective design procedure. In a more detailed review of the resulting designs, the following points can be noted:

- Improving the network performance increases the construction cost of the network; however, the rate of increase in cost is not constant. This is the main point of the multi-objective optimal design.

In scenario 5, it was observed that the performance of the network could be improved by 1 to 2% in this network and almost without imposing additional costs on the basic design;

- Performance in all the scenarios increases linearly with network costs; however, suddenly, at the end of all charts, there is a significant increase in costs without significant changes in system performance;
- As the number of factors influencing the overall performance of the system increases, the range of performance changes becomes more limited and the performance changes become slower and slower. This explanation is more compatible with real conditions because network performance does not change with a slight change in a parameter;
- The run times of the model in scenarios 1 to 5 are 45, 76, 76, 83, and 85 min, respectively. As the definition of performance expands, the run time of the model also increases. The most important factor influencing the run time is the number of decision variables. As the number of decision variables increases, it becomes more and more difficult to achieve a network plan with minimal cost and it takes a long time for the model to achieve its global optimum solution;
- It is necessary to emphasize that the results and findings are based on a simple network. For a more realistic conclusion, it is needed to apply the model to more complicated sewer networks.

It is always possible to achieve good results by spending less cost on the optimal design range. Because, according to all the observations, the slope of the pareto fronts is low at the beginning of the path and even becomes zero in some parts; then, from the point onwards, the increase in costs occurs with a slope beyond the linear slope. This can be important for decision-makers because the results show that in all scenarios, in addition to achieving the basic (cost-based) design, different designs are presented in which performance growth occurs with small changes in costs. These results are not achievable in a single-objective design.

Then, by performing sensitivity analysis on w_1 and w_2 in Eq. (18), changes of the pareto fronts in the final scenario (scenario 5) are examined (Figure 10). Examining the effect of different weight coefficients on the overall performance of the system, it is clear that the effect of these coefficients does not affect the overall rate, but only affects the generated PI. The value obtained for structural performance in all the scenarios is less than the amount of hydraulic performance; thus, changes in structural performance have a greater impact on the overall performance of the network. According to the literature, the effect of different factors on the overall deterioration of a system is very different. In one city, an index may be ineffective, but the same index in another city may have greater effects. Herein, the effect of the coefficient is cleared and the designer can consider important performances with more weight in the design; thus, the proposed model has great flexibility.

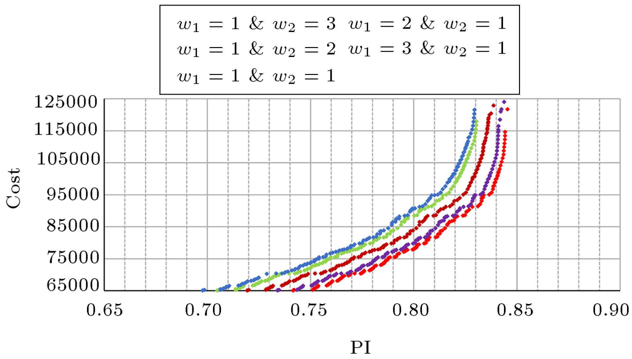

Figure 10. Sensitivity analysis of w_1 and w_2 coefficients in scenario 5.

5. Conclusions

In this research, the following issues were pursued:

- Important factors affecting structural and hydraulic deterioration as system performance deteriorating factors over time were identified;
- A new optimization model with Non-dominated Sorting Genetic Algorithm II (NSGA-II) was developed;
- Penalty curves for velocity, depth of flow, burial depth, and sewer length were developed;
- Structural, hydraulic, and overall performance indices were defined.

The application of this method to a sample network indicates that it is possible to increase the expected performance of the network. It is found that with small changes in the cost-based design, better performance can be achieved while controlling cost increase.

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