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OPTIMAL DESIGN OF SEWER NETWORKS INCLUDING TOPOGRAPHIC CRITERIA AND DROP MANHOLES

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Abstract

Optimal sewer network design is a complex problem that has been widely studied in literature. A methodology published in the literature that has shown great potential is the proposed by Duque, Duque, Aguilar, Saldarriaga. This methodology uses Mixed Integer Programming to select the layout of the network and Dynamic Programming to select the optimal combination of diameters and depths of pipes. Although the methodology showed good performance, two improvements have been implemented in later works. The first one is to consider topographic criteria when selecting the layout. This demonstrated to reduce the sewer network design's costs. The other improvement is the addition of drop manholes in the optimization process. This allowed the methodology to comply with maximum velocity constrains in hilly regions. The present work tested the three methodologies mentioned before in a sewer network located in Bogotá, Colombia to evaluate the contributions and disadvantages of each methodology considering the cost and the hydraulic features of the resulting designs, and the computational resources required with each methodology.

Keywords
Optimal sewer network design, layout selection, hydraulic design, topographic criteria, drop manholes.

1 INTRODUCTION

Sewer network design is a problem that is divided into two subproblems: the layout selection and the hydraulic design. In the layout selection, the structure of the network is defined; this includes the flow direction, flow rate and type of connection of pipes. In the hydraulic design the diameter and upstream and downstream invert elevation of pipes is defined.

Due to the complexity of both subproblems and the immense number of alternatives that exists to design a sewer network, finding the optimal design it's been a challenge for the researchers in this field. For this reason, many approaches have been proposed to try to find the optimal or a near-optimal design of a sewer network. For example, Li and Matthew [1] proposed the searching direction method for the optimal selection of the layout and used discrete dynamic programming (DDDP) for the hydraulic design. Haghighi [2] proposed an adaptative method entitled loop-by-loop cutting algorithm to solve the layout selection and used a discrete differential dynamic programming model for sizing the pipes. Later, Haghighi and Bakhshipour [3] used the loop-by loop cutting algorithm for the layout selection and tabu search (TS) for the hydraulic design. After that, Duque et al. [4] used mixed-integer programming (MIP) for the layout selection and Dynamic Programming (DP) for the hydraulic design.

This last approach achieved the designs with the lowest cost at the time when it was published in two sewer network benchmarks studied in the literature. In later works, some extensions have been added to improve the approach of Duque et al. For example, Saldarriaga et al. [5] proposed a methodology to include topographic criteria in the layout selection model which achieved designs with lower costs than the work of Duque et al. Also, in a methodology that will be described later in this work, drop manholes are included in the optimization process. This is especially important in hilly regions where drop manholes are necessary to comply with maximum velocity constrains and to dissipate flow energy in the system.

In the present work, a comparison between the three methodologies mentioned before is done in order to identify their advantages and disadvantages related with the construction cost and the hydraulic features of the resulting designs. The three methodologies were tested using a sewer network located in Bogotá, Colombia, with a modified ground elevation to simulate a hilly region and in this way, to include the possibility of having drop manholes in the designs.

2 DESIGN METHODOLOGIES

2.1 Sewer network design methodology proposed by Duque et al. [4]

Duque et al. proposed an iterative scheme to find a near-optimal solution for the sewer network design problem. As mentioned before, this problem is composed by two subproblems: the layout selection and the hydraulic design. Each iteration of the methodology is composed by the solution of the layout selection and the hydraulic design, and with each iteration the construction cost of the network is refined.

With this methodology, the layout selection problem is modelled using graph theory. The input of the problem is an undirected graph composed by nodes and arcs. The nodes represent each manhole of the sewer network with its respective x and y coordinates, ground elevation, and inflow. The arcs represent the connection between two manholes that depend on the direction and the type of connection. There are two types of connection in pipes, outer and inner branch pipes. Outer branch pipes are the first pipe in a series, while the inner branch pipes are the rest of the pipes. These types of connection are represented as t_1 and t_2, respectively.

Since the connection between two manholes can have to possible directions (i.e., $i \rightarrow j$ or $j \rightarrow i$) and two possible types of connection (i.e., t_1 or t_2), there are four possible arcs between a couple of manholes as is shown in Figure 1.

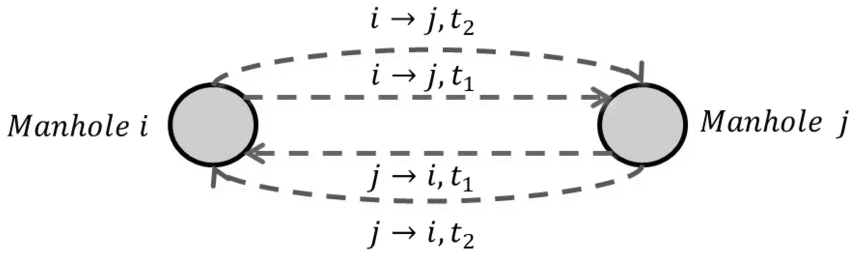

Figure 1. Arcs between two manholes.

With the given undirected graph, linear optimization is used to find the layout of the sewer network. This is, to establish the flow direction, type of pipe connection, and flow rate in pipes. This is done using two decision variables: x_{ijt} and q_{ijt}. x_{ijt} is a binary variable that takes the value of one (1)f the pipe from manhole *i* to manhole *j* and type *t* is part of the layout selection. q_{ijt} is a continuous variable that represent the flow rate that is transport in the pipe from manhole *i* to manhole *j*. The linear optimization model also considers the constrains that guarantee a feasible layout and the objective function.

The objective function of the model should be the minimization of an equation that represents the construction cost of the network. However, the construction cost depends on the diameters and excavation depths of pipes, which are unknown in the layout selection subproblem. For this reason, the objective function that Duque et al. proposed for this subproblem is an approximation of the construction cost of the sewer network. This approximation is done with a linear regression between the flow rate and cost of pipes. Nevertheless, in the first iteration the cost of pipes is also unknown, therefore, in the first iteration the linear regression coefficients are random values, but with the following iterations their values are refined. Equation (1) presents the objective function where c_{ij} and a_{ij} are the linear regression coefficients, and x_{ijt} and $q_{ijt}$are the decision variables of the model.

$$min\left(\sum_{t \in \mathcal{T}} \sum_{(i,j) \in \mathcal{A}_L} c_{ij} q_{ijt} + \sum_{t \in \mathcal{T}} \sum_{(i,j) \in \mathcal{A}_L} a_{ij} x_{ijt} \right) \tag{1}$$

After selecting the layout of the network, the hydraulic design is performed. In this subproblem the diameters and depths of the pipes are defined. This was done by Duque et al. using a Shortest Path Algorithm. In this kind of algorithm, the problem is modeled as a directed graph where each arc has a cost associated and the objective is to find the path of arcs with the minimum cost.

To model the hydraulic design as a Shortest Path Algorithm, Duque et al. proposed a graph composed by nodes and arcs. The nodes represent the possible combinations of diameters and depths, while the arcs represent the diameter and depth of a specific pipe. Each manhole of the network has associated a group of nodes. The arcs connect two nodes from two different manholes representing a specific pipe. Figure 2 shows an example of the arcs and nodes that represent a pipe between two manholes. In this example, each manhole has 9 nodes that correspond to the possible combinations of 3 diameters and 3 depths. d_1, d_2 and d_3 are different diameters, and Z_1, Z_2 and Z_3 are different depths. The arrows represent the feasible arcs that model the pipe. Note that the upstream node can never be connected with a downstream node that has a smaller diameter or a shallower depth. Also, in the example there are only 3 diameters and 3 depths, but, in the methodology, there could be as many diameters and depths as desired.

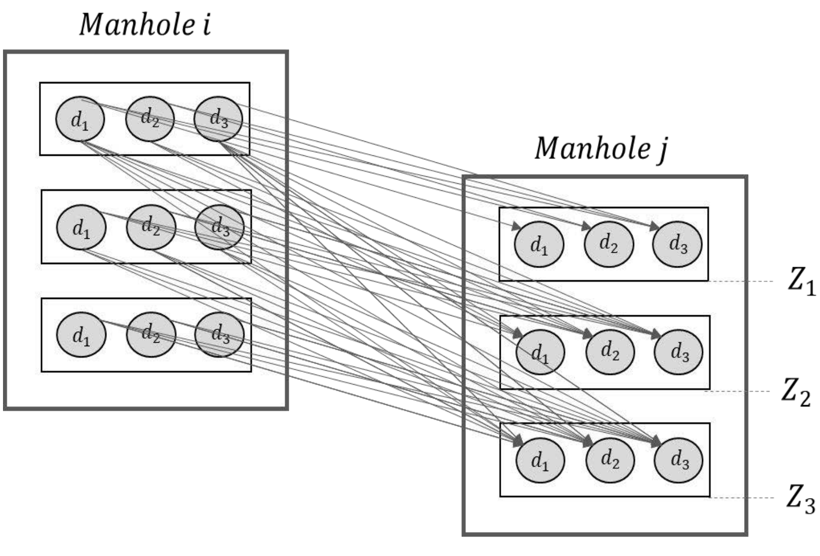

Figure 2. Example of nodes and arcs that represent a pipe.

Each arc of the model has a cost that depend on the diameter and depth of its downstream node. Considering this cost, the Shortest Path Algorithm selects the path of minimum cost, this is, the optimal combination of diameters and depths of the sewer network.

In the hydraulic design problem, the real cost of the pipes is known because the diameters and invert elevations are known. With this information, the linear regression of the objective function of the layout selection is done and with each iteration, the objective function is improved. As a consequence, with each iteration the real cost of the network is reduced until the methodology converges. For this reason, around 10 to 30 iterations must be performed to find the solution of the sewer network design problem with this methodology.

2.2 Layout selection including topographic criteria proposed by Saldarriaga et al. [5]

Since the methodology proposed by Duque et al. requires a random initialization of the objective function in the layout selection, Saldarriaga et al. proposed a modification to improve this equation. The improvement consists in the addition of the parameter b_{ijt} in the objective function as is shown in Equation (2). The purpose of this parameter is to consider the topography of the land in the layout selection and, in this way, that the direction of the pipes follows the land's slope, since this reduces the required excavation depth, and therefore, reduces the cost of excavation.

$$min\left(\sum_{t\in\mathcal{T}}\sum_{(i,j)\in\mathcal{A}_L} c_{ij}q_{ijt} + \sum_{t\in\mathcal{T}}\sum_{(i,j)\in\mathcal{A}_L} a_{ij}x_{ijt} + \sum_{t\in T}\sum_{(i,j,t)\in A_L} b_{ijt}x_{ijt}\right) \tag{2}$$

The parameter b_{ijt} is calculated for each arc in the network (recall the existing arcs in Figure 1). This means that for a pipe, four parameters b_{ijt} are calculated depending on the direction and the type of connection of the pipe. From these four values of b_{ijt}, the linear optimization model selects the one that has the minimum value, and in this manner, the direction and type connection of the pipe is stablished.

As mentioned before, it is preferred that the pipes follow the land's slope. For this reason, the arcs that follow this direction have a b_{ijt} with lesser value. Regarding the type of connection, it was found that trying to minimize the outer branch pipes let designs with lower costs, so the parameter b_{ijt} tries to give priority to the inner branch pipes. The value of b_{ijt} is established using three different topographic criteria.

2.2.1 Topographic criterion 1

This criterion is defined by the multiplication of the land slope where the pipe is located and -1. In this way, the arcs that follow the land slope will be prioritized because its parameter b_{ijt} will have a negative value and this is preferred by the objective function since it is a minimization function.

Also, to give priority to the inner branch pipes, the outer branch pipes are multiplied by a penalty that increases the value of b_{ijt}. A sensitivity analysis was done to stablish that 0.65 is a good value to use as a penalty when the slope is positive, and 1.65 when the slope is negative. Note that the penalty must be different depending if the slope is negative or positive because, in the first case, b_{ijt} will be a negative value, so to increase this value it must be multiplied by a number between 0 and 1. In the second case, b_{ijt} will be a positive value so to increase this value, it must be multiplied by any number greater than 1.

To resume, Equation (3) and (4) presents how b_{ijt} is calculated using criterion 1 in inner and outer branch pipes, respectively, where s is the land slope and μ is the penalty for outer branch pipes.

$$b_{ijt_2} = s_{ijt_2} * (-1) \tag{3}$$

$$b_{ijt_1} = s_{ijt_1} * (-1) * \mu \quad (4)$$

2.2.2 Topographic criterion 2

This is a power-based criterion that is calculated the same way as criterion 1 but the land slope is also multiplied by the length of the pipe. The penalty for the outer branch pipes is the same as in criterion 1. Equation (5) and (6) presents how b_{ijt} is calculated using criterion 2, where L is the length of the pipe.

$$b_{ijt_2} = s_{ijt_2} * (-1) * L_{ij} \quad (5)$$

$$b_{ijt_1} = s_{ijt_1} * (-1) * L_{ij} * \mu \quad (6)$$

2.2.3 Topographic criterion 3:

This criterion was proposed specially for flat regions since it does not depend on the land slope. With this criterion b_{ijt} is calculated as the distance between the downstream manhole of the pipe and the outfall of the sewer network. With this criterion there is not a penalization in the outer branch pipes.

The layout selection model must be executed using each of the three topographic criteria at the time. This means that three iterations must be done and in each one of them a different layout will be obtained. With each layout, a different hydraulic design is achieved. The design with the lowest cost is used in a fourth iteration where the excavation depth is penalized to try to reduce the cost of the design even more.

2.2.4 Iteration with penalization in excavation depth

In this iteration, two cost are considered: the cost per unit length of pipes and the cost of the extra excavation that must be done if an arc is chosen compared to the average installation slope of the design with the lowest cost obtained with the topographic criteria.

For the inner branch pipes, the cost per unit length is considered in the linear regression coefficients (c_{ij} and a_{ij}) of the objective function. Regarding the cost of the extra excavation, if the land slope where the pipe is located is smaller than the average installation slope, b_{ijt} is the extra excavation cost. In the opposite case, b_{ijt} is calculated as the extra excavation cost multiplied by -1.

In the case of the outer branch pipes, the cost per unit length is almost always the same because they tend to have the smallest diameter and depth. For this reason, the cost per unit length is not included in the linear regression and it must be included in the value of b_{ijt}. In outer branch pipes, when the slope of the pipe is smaller than the average installation slope, b_{ijt} is the average cost per unit length multiplied by the length of the pipe. In the opposite case, b_{ijt} is the sum of the extra excavation cost and the cost of the pipe.

With this method to penalize the excavation depth, the layout selection model tries to find a solution that reduces the extra excavation. However, the hydraulic design obtained from the resulting layout of this iteration has not always a lower cost then the designs from the topographic criteria. For this reason, from the four iterations done with the methodology, the one with the lowest design should be selected as the solution of the sewer network design problem.

2.3 Hydraulic design including drop manholes

Designing a sewer system in hilly regions is a challenge because high slopes induce to high velocities that exceed the maximum velocity constrain. If this constrain is no complied, pipes and other sewer structures could be damaged. To comply with the mentioned constrain and to dissipate the flow energy in sewer networks, drop manholes are used. These structures are vertical manholes where the upstream pipe is in a higher level that the downstream pipe. The difference between the level of those pipes is the drop height that helps with the dissipation of the flow energy.

As part of this work, a methodology to include drop manholes in the sewer network design problem was introduced. This methodology consists in the addition of a new type of arc that represent the possibility of having drop manholes in the network. These arcs have a vertical direction and their downstream node have a greater depth than their upstream node. Also, the length of the arcs represents the drop height of the drop manhole. Figure 3 presents an example of an arc that represent a drop manhole where its upstream node has a diameter d_2 and an excavation depth Z_1, and its downstream node has the same diameter but an excavation depth of Z_2.

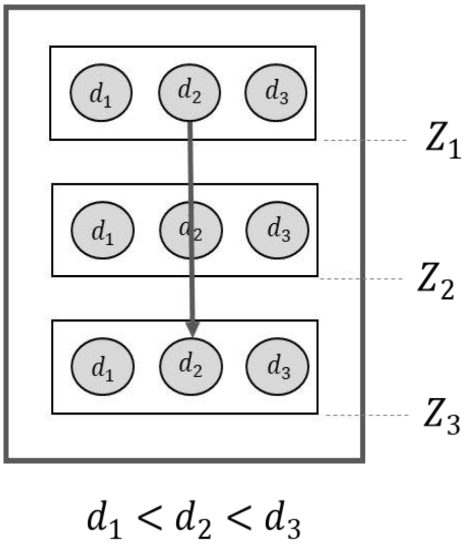

Figure 3. Example of an arc that represents a drop manhole.

Since the new types of arcs represent drop manholes and the original arcs of the methodology represent pipes, the cost function is different for each type of arc. In the case of the latter, their cost function depends on the diameter and depth of the pipe, but in the case of the arcs that represent drop manholes, their cost function must represent the cost of installing a drop manhole in the network.

The Shortest Path Algorithm works the same way as in the original methodology, it finds the path of arcs with the minimum cost that represent the hydraulic design of the network. With the addition of the new type of arcs, the algorithm needs to evaluate a greater number of arcs to find the optimal solution.

3 CASE STUDY

To test the three methodologies, a sewer network labelled Chicó was used. This network is located in Bogotá, Colombia and is composed of 109 manholes and 160 pipes that transport a total flow rate of 1.525 m^3/s. The ground elevations of the manholes were modified to have a slope of 5%. This was done to simulate a hilly region where drop manholes can improve the cost of the sewer network designs. Figure 4 illustrates the structure of the Chicó sewer network with the respective location of the outfall.

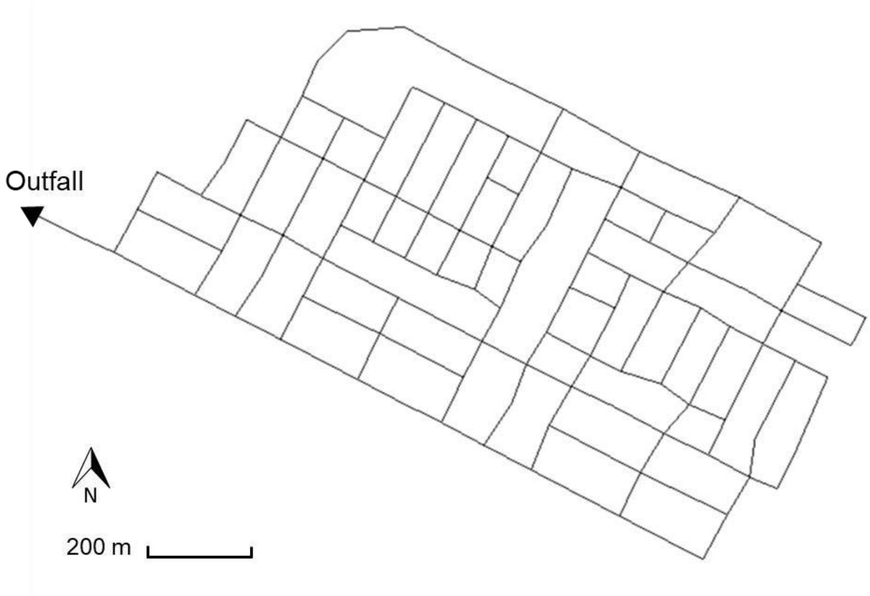

Figure 4. Chicó sewer network.

All the designs obtained with the three tested methodologies comply with hydraulic constrains that allow an adequate operation of the sewer network. For this work, the constrains proposed by Li and Matthew [1] were used. This constrains are presented in Table 1.

Table 1. Hydraulic constrains for the sewer network design

Constrain	Value	Condition
Minimum diameter	0.2 m	Always
Maximum filling ratio	0.6	$d \leq 0.3$ m
	0.7	0.35 m $\leq d \leq 0.45\ m$
	0.75	0.5 m $\leq d \leq 0.9\ m$
	0.8	$d \geq 1\ m$
Minimum velocity	0.7 m/s	$d \leq 0.5$ m and Flow rate > 0.015 m$^3/s$
	0.8 m/s	$d > 0.5$ m and Flow rate > 0.015 m$^3/s$
Maximum velocity	5 m/s	Always
Minimum gradient	0.003	Flow rate $< 0.015\ m^3/s$
Minimum depth	1 m	Always

Also, the list of available diameters used is: {0.2, 0.25, 0.3, 0.35, 0.38, 0.4, 0.45, 0.5, 0.53, 0.6, 0.7, 0.8, 0.9, 1.0, 1.05, 1.20, 1.35, 1.4, 1.5, 1.6, 1.8, 2, 2.2, 2.4} in meters. And the material of the pipes used was concrete with a Manning's n of 0.014.

To measure the construction cost of the sewer networks, two cost function were used, one for the pipes and another one for the drop manholes. The cost function used for the pipes was proposed by Maurer et al. [6] and is presented in Equation (7), where C is the construction cost of a pipe in USD, h is the average excavation depth of the pipe in meters, l is the length of the pipe in meters, and α and β are coefficients that depend on the diameter of the pipe.

$$C = (\alpha h + \beta) * l \tag{7}$$

For the cost of the drop manholes, Equation (8) was used, where C_{dmh} is the cost of a drop manhole in USD, h is the excavation depth of the drop manhole in meters, and d is the diameter of the downstream pipe of the drop manhole.

$$C_{dmh} = 4354.38 - 776.76h + 5404.52d - 6370.59hd + 870.05h^2 + 12820.76d^2 \tag{8}$$

4 RESULTS AND DISCUSSION

Table 2 presents the results of the designs achieved with each methodology. The table includes the construction cost of the sewer network, the most important hydraulic constrains in hilly regions, the number of drop manholes in the design and the number of iterations required in each methodology.

Table 2. Results of the design of the Chicó sewer network.

Design	Methodology	Constructi on cost (USD x10^6)	Maximum filling ratio (%)	Maximum velocity (m/s)	Maximum depth (m)	N° of DM	N° of iterations
1	MIP and DP	$ 8,96	74.75	4.97	7.80	0	23
2	MIP with TC and DP	$ 7,67	74.77	4.94	4.20	0	4
3	MIP with TC and DP with DM	$ 7,62	74.77	4.98	3.00	2	4

MIP: Mixed Integer Programming.
DP: Dynamic Programming.
TC: Topographic criteria.
DM: Drop manholes.

Regarding the construction cost, the design with the highest cost is the one obtained with the methodology of Duque et al., which is the expected result because it is the original methodology without any improvement. When including the topographic criteria in the layout selection model, the cost of the design is reduced in 14.39%, which is equivalent to $ 1.29 x 10^6 USD. Also, when including the possibility of designing with drop manholes, the cost is reduced even more. It is reduced in 14.89% compared with the original design.

The three designs comply with all hydraulic constrains, which are important to guarantee an adequate operation of the sewer network. Regarding the maximum filling ratio and the maximum velocity, the three designs achieved values that are close to the maximum allowed, that is, 75% for the maximum filling ratio, and 5 m/s for the maximum velocity.

In contrast, the maximum depth is very different in each design. The design with the highest depth is also the one with the highest cost. The use of the topographic criteria to try to select a layout that follows the land slope reduces the maximum depth in 3.6 meters. In addition, the use of drop manholes can also let to a reduction of the maximum depth, although it is not as significant as the reduction achieved with the topographic criteria.

It is important to note that the only design that includes the possibility of having drop manholes is the third one. Two drop manholes were obtained in the design with this methodology. Both are located just before the outfall, and both have 1.1 meters of drop height.

Lastly, including topographic criteria in the layout selection model allows a significant reduction of the required number of iterations. In the original methodology, 23 iterations were needed, while with the other methodologies, only 4 iterations were required. Figure 5 illustrates the cost achieved in each iteration of the three evaluated methodologies.

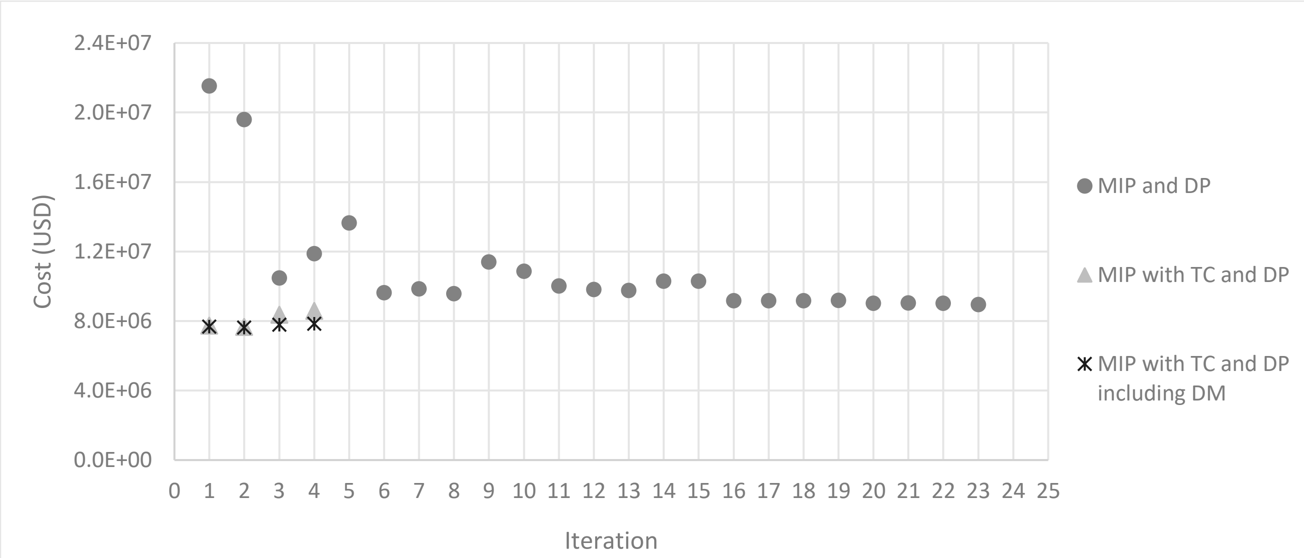

Figure 5. Cost of the designs in each iteration of the methodologies.

Figure 5 shows that the MIP and DP methodology converges, this means that the cost of the designs is refined with each iteration. This is not the case with the methodologies that uses topographic criteria, since with these methodologies each iteration uses a different strategy to follow the land slope. As it can be seen, considering topographic criteria in the model not only reduces the iterations required to find a near-optimal solution, but also the 4 iterations achieved with this methodology have a lower cost than the best solution from the original methodology.

Also, when analysing the iterations with the methodology that include drop manholes it can be seen that the cost of the designs is lower, but the reduction is not very significant. Furthermore, the addition of drop manholes to the model does not increment the number of iterations, but it does increment the computational time in each iteration because the Shortest Path Algorithm needs to evaluate a greater number of arcs, since the drop manholes are modelled as arcs.

5 CONCLUSIONS

In the present work three methodologies for the optimal design of sewer networks were compared using as a case study a real sewer network located in Bogotá, Colombia. The first methodology consists in an iterative scheme were the layout selection and hydraulic design models are embedded. With each iteration the cost of the design is reduced. The layout selection model is solved using MIP, while the hydraulic design model is solved using DP, or more specifically, a Shortest Path Algorithm that guarantees to select the optimal combination of diameters and excavation depths for a given layout.

The second methodology is an extension of the methodology previously described. The extension consists in the addition of topographic criteria to the layout selection model to try to follow the land slope. Using these criteria, the methodology does not require an iterative scheme because the layouts obtained following the land slope let to great hydraulic designs. This means that the number of iterations is reduce using topographic criteria.

The third methodology is also an extension of the original methodology, and it also includes topographic criteria. The contribution of this methodology is that it includes the possibility of having drop manholes in the hydraulic design. These structures are important in hilly regions where it is difficult to comply with maximum velocity constrains.

To compare the three methodologies, the Chicó sewer network was used. This network has been used as a case study in previous works in the literature, but in the present work it was important to simulate a hilly region to study the effect of drop manholes in the designs. For this reason, the ground elevation of the network was modified to have a land slope of 5%.

From the results, the main conclusion is that considering topographic criteria in the model reduces the construction cost of the network in a significative way and also reduces the required amount of iterations to find a near-optimal solution. This is because the topographic criteria try to select the direction of pipes in the layout in order to follow the land slope, this allows a reduction of the maximum depth required by the pipes, which also reduces the construction costs.

When using the third methodology, two drop manholes were obtained in the design. These structures allowed a reduction of the maximum depth required in the network, for this reason, the cost was also reduced when using the methodology with drop manholes, although the reduction of costs was not as significant. Also, the addition of drop manholes in the model does not increment the number of iterations, but it increments the computational time in each iteration.

In the case study used, the three methodologies achieved to comply with all hydraulic constrains that are important to guaranty a satisfactory operation of the sewer network. The designs obtained had similar maximum filling ratios and maximum velocities, which means that, for the case study used, the drop manholes did not have an important impact on the compliance of constrains. However, the drop manholes did help to reduce the excavation depth and, therefore, the construction cost of the network.

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