

Costs Functions Proficiency over the Urban Drainage Networks Optimal Design

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ABSTRACT

The urban drainage networks optimal design objective function must represent accurately the real construction costs of these systems. This design problem involves two sub problems which require a specific cost function. For the layout selection problem, a cost function in terms of the flow rate and direction is needed, since there is no information about the diameter, depth, and slope of the pipes. A good estimation of the layout cost function is needed to find the minimum-cost urban drainage network design. The optimal hydraulic design of the network requires the best layout selection. In this paper some cost functions are tested using the urban drainage network optimal design methodology proposed by Duque N. et al. (2015) [1], on part of a real network located in Bogota, Colombia. Afterwards, a sensitivity analysis is performed to determine the effect of each cost function over the layout selection and hydraulic design of the network. Moreover, this analysis aims to evaluate the cost functions proficiency and robustness, when changing parameters such as the filling ratio and the pipes material.

Keywords: Urban Drainage Networks, Optimization, Layout, Cost Function.

1. INTRODUCTION

The urban drainage networks design problem needs to be solved from an economic point of view, taking into account that the cheapest solution should be chosen among all the possible solutions. Therefore, an optimization methodology [1] is used to obtain the minimum construction costs design that satisfies all hydraulic restrictions established by the national technical regulations.

Due to the high number of variables that must be considered for the solution of the urban drainage network design problem, the literature proposes to divide the problem in two sub problems: the layout selection and the hydraulic design. The layout selection defines the flow direction in the pipes between the manholes, and the design flow rate. While the hydraulic design defines the diameter of pipes from a set of available commercial diameters, and the excavation depth needed to place them. The objective function seeks to minimize the total construction costs, taking into account that the results for the layout selection are used as input data for the hydraulic design problem.

In addition, Li et al. (1990) used nonlinear programming (NLP) models in order to determine both topographic and hydraulic factors such as the flow rate, diameters and slopes of the pipes in the network [2]. In this approach the authors divided the problem into two stages. The first stage corresponds to the optimization of diameters and slopes of the pipes, together with the localization of pumping stations. In the second stage, all variables remain constant and the flow rate is gradually

modified, searching for the pipes that minimize costs function, using Dijkstra's Shortest Path Algorithm.

However, the most popular method among the different authors in the literature is the Genetic Algorithms (GA). Haghghi, A. and Bakhshipour, A., (2012) used GA to solve the urban drainage networks hydraulic design, determining the pipe diameters and excavation depths [3]. Other authors have combined different methodologies with the GA to increase the methods efficiency. Cisty M., (2010) proposed an alternative that uses GA with Linear Programming (LP) [4]. Pan and Kao, (2009) combined GA with Quadratic Programming [5]. Other heuristic methodologies for the optimal design of urban drainage networks, such as Ant Colony Optimization (ACO), Simulated Annealing (SA) and Tabu Search (TS) algorithms have also been used.

This work wants to present an statistical analysis over the design of real network, by changing different parameters such as the costs equations, the pipes materials, the maximum filling ratio and the number of segments used to linearize the objective function for the layout selection model established in the design methodology proposed by Duque et al. (2016) [1].

2. METHODOLOGY

For the solution of the urban drainage networks design problem, Duque proposed a Minimum-Cost Flow Model for the layout selection sub problem, which defines the type of pipe (initial or continuous), the flow direction and design flow rate. The input parameters for this problem are the Cartesian Coordinates in the three dimensions (x , y and z) of each manhole and their inflow. Subsequently, the hydraulic design of the corresponding layout, determines the diameter and excavation depth for each pipe that belongs to the network, modeling this second problem as a Shortest Path Problem, performing the Bellman-Ford algorithm over a graph modeling framework. as the hydraulic design problem needs as input data the network's layout, the pipes materials and the kinematic viscosity of water [6].

This work aims to analyze the performance of the methodology over large urban drainage networks, using different costs functions. In this way, the idea is to use different values for some parameters and analyze their influence over the total construction costs. In the first place, different costs functions are implemented, in order to observe the effect over the layout selection and hydraulic design of a specific network.

2.1. Cost Functions

The first equation implemented, in the layout selection and hydraulic design problems, was proposed by Maurer, M. et al [2]. This expression allows to estimate the construction costs of an urban drainage network in dollars (USD). This equation was dimensioned through a hydrological and demographic analysis, and is described by equation (1). The cost per section C_{ij} takes into account the cost of the pipes and their installation, and is expressed in terms of the diameter d_{ij} and the excavation depth h_{ij} , as shown in equations (1) to (3).

$$C_{ij} = \alpha h_{ij} + \beta \quad (1)$$

$$\alpha = 1.02 * 10^{-3} d_{ij} + 127 \quad (2)$$

$$\beta = 0.11 * 10^{-3} d_{ij} + 35 \quad (3)$$

The second cost function proposed by Marchionni, M. et al. [3] was implemented for the networks design. This equation takes into account the physical characteristics of the ground, the pipes material and the excavation depth of pipes and manholes. Equation (4) represents this costs expression in euros (EUR). It was estimated from a multiple linear regression over the real constructions costs of 17 different urban drainage networks. The total construction costs per section C_{ij} includes the cost of installation per linear meter of the pipes and per manhole, which depend on the diameter of the pipe d_{ij} , the average excavation depth h_{ij} and the depth of the upstream manhole h_j .

$$C_{ij} = C_{pipe} + C_{manhole} \quad (4)$$

$$C_{pipe} = 203.3111 + 0.1254d_{ij} + 131.4391h_{ij} + 0.0440d_{ij}h_{ij} \quad (5)$$

$$C_{manhole} = 1.6928 + 3.6231h_j \quad (6)$$

The third equation implemented was proposed by Moeini, R [9], where the pipes and manholes costs are considered. The Equation (7) calculates the cost C_{ij} in Iranian Rials (IRR), and was deduced through a heuristic methodology for the design of drainage networks using ACO. This equation is also in terms of the diameter d_{ij} , the average excavation depth h_{ij} and the downstream manhole depth h_j per section.

$$C_{ij} = C_{pipe} + C_{manhole} \quad (7)$$

$$C_{pipe} = 10.93e^{3.43d_{ij}} + 0.012h_{ij}^{1.53} + 0.437h_{ij}^{1.47}d_{ij} \quad (8)$$

$$C_{manhole} = 41.46h_j \quad (9)$$

2.2. Sensitivity analysis of the design due to changes in the pipes material

The pipes in an urban drainage networks represent the 70% of the total area in average [2]. This component is the biggest fraction of the construction costs. In this way, it is important to notice the effect of changing physical characteristics of the pipes over the hydraulic design results. One parameter that affects the hydraulic design of the network is the pipe material, since the roughness coefficient is involved in the estimation of the flow rate.

For this reason, this work presents some numerical examples using different materials with different roughness coefficients, in order to observe changes in the layout, and subsequently in the hydraulic design of an urban drainage network. Actually, there are multiple pipes materials that can be used in the construction of urban drainage networks. In this case the three most common materials were used (PVC, GRP and concrete), which have different physical and structural characteristics that must be considered from the economic point of view. In other words, it is important to conclude about the effect of the pipe material over the total construction costs.

To perform the sensitivity analysis, four roughness coefficients were used. PVC pipes were modeled using a roughness coefficient (k_s) of 0.0015 mm, as well as GRP pipes were modeled with a roughness coefficient of 0.023 mm, concrete 1 with a roughness coefficient of 1 mm and concrete 2 with a roughness coefficient of 0.3 mm.

2.3. Sensitivity analysis of the design due to changes in the maximum filling ratio in the pipes

In the methodology proposed by Duque [1] is important to define the maximum filling ratio in the pipes, for the definition of the hydraulic design and layout selection. This allows to make a coherent connection between the two models and estimate in a precise way the construction costs.

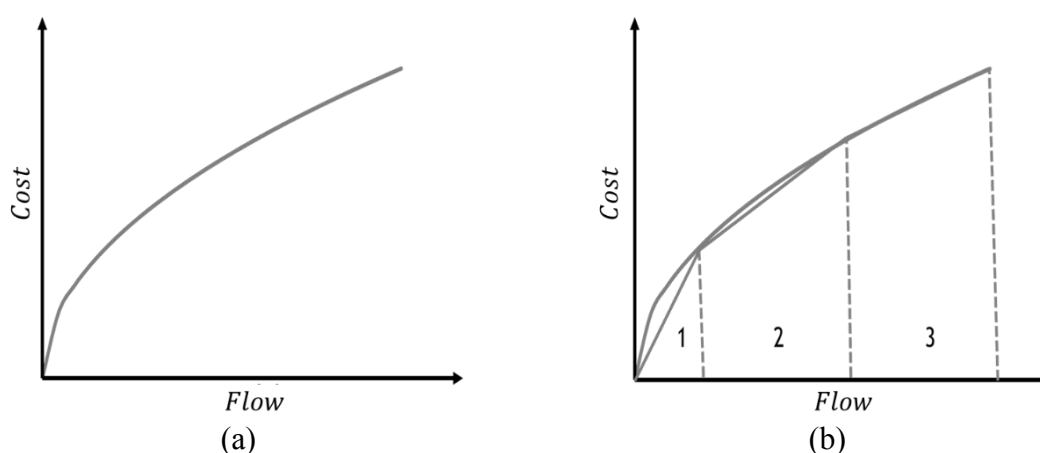
In this way, this project wants to test how the assumption of the maximum filling ratio may condition the construction cost of a specific network. Therefore, the idea is to implement different values for the maximum filling ratio restriction both in the hydraulic design model, and in the objective function of the layout selection model. The maximum filling ratio that will be used varies between 75% and 100%, increasing with a 5% step.

2.4. Sensitivity analysis over the linear approach of the objective function in the layout selection

Based on the implementation proposed by Duque that suggests a linear approximation of the objective function due to the selection layout model requirements, then this project intends to make an analysis of the impact that have the number of line segments that are used to simulate the cost function.

In the Graph 1(a) is observed as the relationship between the cost of a section and the design flow is not linear. Thus, the methodology of Duque modeled the curve through segments of straight lines. In the case of the Graph 1(b), three straight lines are used. In this way, increasing the number of lines is expected a higher computational time required to obtain the results of a layout.

In conclusion, the idea is understood how this parameter can affect the construction cost of the network, for this reason exists two scenarios, the first with five (5) lines and the other with ten (10) lines for each section of the network.



Graph 1. (a) Cost function dependent of the flow in a section; (b) Linear approaching of the cost function.

2.5. Statistical analysis

Finally, to conclude about the performance of the methodology proposed by Duque and the proficiency of the cost equations against the different proposed scenarios for the analysis, a

statistical analysis is implemented, which allows to define the probability distribution of each of the equations and the variability against the studied parameters.

Now, to perform such analysis is necessary the use of different tools as histograms and box diagrams, which graphically allow to see the variability and the effect of the cost of the drainage network against the parameters explained in sections 2.2, 2.3 and 2.4. However, to make a comparison of all the implemented scenarios, independent of the cost equation, should be a standardization of costs, taking into account that the costs of construction of each of the implemented scenarios are in different currencies. The equation 10 shows the expression of standardized cost Z_i which allows this comparison.

$$Z_i = \frac{\text{Cost } i}{\text{Average cost}} \quad [10]$$

In total, there are 144 scenarios, where each one corresponds a cost equation, a material pipe, a maximum filling ratio and a defined number of segments to the linear approximation.

3. ANALYSIS OF RESULTS

In this paper, to test the methodology is implemented a real urban drainage network located in Bogotá, Colombia, which has 110 manholes and 160 pipes with a steep ground. Where the hydraulic design was designed with Darcy-Weisbach resistance equation, and a set of commercial diameters available on meters: 0.20 m, 0.35 m, 0.45, 0.60 m, 0.70, 0.80 m, 0.90 m, 1.10 m, 1.20 m, 1.50 m, 1.80 m.

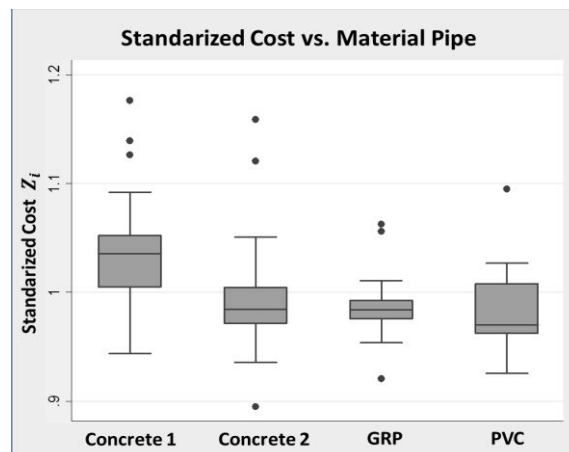
Also, the hydraulic constraints for the design are presented in Table 1. Other input parameters as the coordinates of the manholes and their input flows are presented in the article "An Exact Methodology for Sewer Systems Design" [1].

Table 1. Hydraulic Design Constraints

Constraint	Value	Condition
1 Minimum diameter	200 mm	Always
2 Maximum filling ratio	0.75 – 1.00	
3 Minimum wall shear stress	2 Pa	$d \geq 450\text{cm}$
4 Minimum velocity	0.75 m/s	$d < 450\text{cm}$
5 Maximum velocity	5 m/s	$k_s > 0.0001$
	10 m/s	$k_s < 0.0001$
6 Minimum slope	The one for which the minimum velocity and shear stress are obtained.	
7 Maximum slope	The one for which the maximum velocity is obtained.	

3.1. Results of the material of the pipe, maximum filling ratio and number of segments for the linear approaching

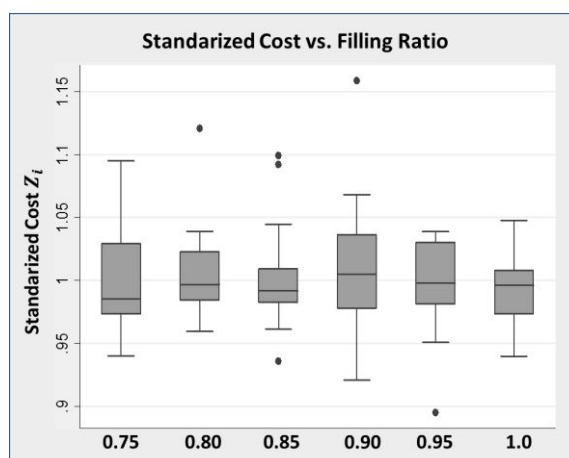
The example drainage network was implemented with each of the cost equations, after it is possible to classify the 144 scenarios raised depending on the material of pipe, and thus the following results were obtained:



Graph 2. Standardized cost depending of the material pipe

From the Graph 2, it can be concluded that the GRP and PVC are the best options for implementing a network because these materials minimize the construction cost of the network and at the same time has a lower variability against the change of the different hydraulic parameters explained. The reason for this situation is that these materials do not apply a resistance to the fluid, and with small diameters is possible to maximize the filling ratio in the pipes.

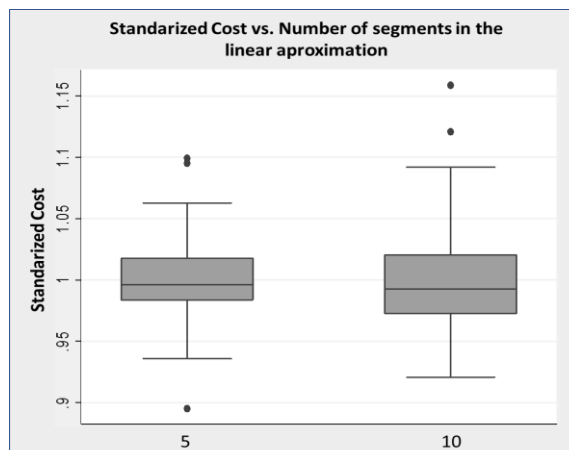
In the same way as the previous parameter, the scenarios explained were classified in the 6 defined intervals for the maximum filling ratio, and the following results were obtained:



Graph 3. Standardized cost depending of the maximum filling ratio

The Graph 3 confirm that in average the construction costs are minimized with a filling ratio of 90%. The minimum cost can be a 92% of the average cost. However, the less variability occurs with ratios between 80% and 85%. Taking into account that the highest costs occur with a ratio of 75%, and these may be 9% higher than the average. Also, it should be noted that while is established a maximum filling ratio of 100%, in the hydraulic design the real filling ratio in the pipes never attain this maximum point, due to the conditions of the topography and other restrictions of the model.

Finally, the implemented scenarios are classified depending of the number of line segments that were implemented in the linear approaching to the objective function in the layout selection model, and the following results were obtained.



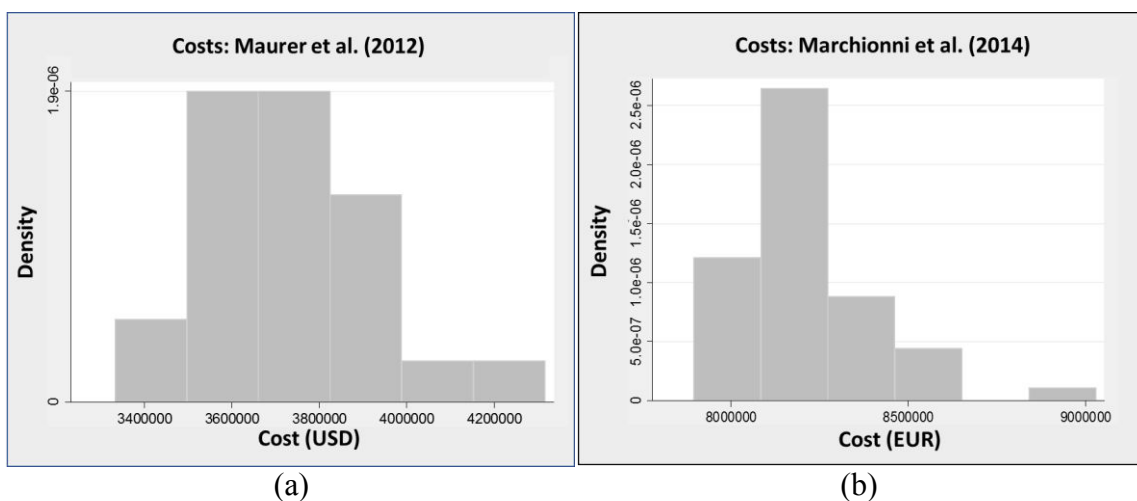
Graph 4. Standardized cost depending of the linear approaching in the layout selection.

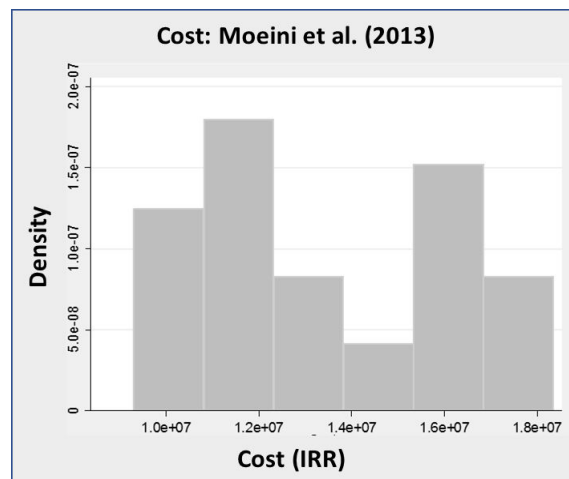
From Graph 4, it is possible to observe that in the most of cases between most lineal segments are divided the objective function greater will be the precision in the estimation of costs, and is therefore more likely that minimizing costs on average, noting that this situation always occurs independent of the equation of cost implemented.

Also, it is possible to affirm that the number of segments are higher, the construction cost can be lower. However, among less is this number also will be the variability of the cost of the different scenarios, and the computational time required to obtain a layout will be shorter.

3.2. Probability distribution of the costs functions

Statistical tools as histograms were used to define the probability distribution of the construction costs of an urban drainage network, using different scenarios, in order to analyze the variability and the robustness of each equation.





(c)

Graph 5. Standardized cost depending of the linear approaching in the layout selection.

Based on previous histograms, and some hypothesis tests were performed to verify the distribution of the costs equations. It is possible to conclude that usually due to the central limit theorem, the construction costs of networks will tend to have a Normal distribution. However, based on the previous results and the histograms, it can be said that the standard deviation depends on the costs equation. From Graph 5, it can be inferred that Marchionni's equation may be the more robust and less variable than Moeini's equation, which minimizes the costs, but has a higher variability. Furthermore, Maurer's equation saves the perfect balance between the costs optimization and the standard deviation.

4. CONCLUSIONS

The layout and hydraulic design are directly affected by the cost equation implemented. Depending on the nature of the equation it can obtain different results for the diameters and excavation depths, as wells as the flow directions and type of pipes.

The Maurer's equation has a greater potential to design networks larger than the numerical example, because this requires less computational time and low resource usage. According to the statistical analysis, it can be said that Maurer's equation is the most robust, because it has less variability to different changes in the parameters, and therefore would be more useful to implement in future work.

The pipe material is a parameter that influence both the layout and hydraulic design of the network. It is possible to conclude that materials such as PVC and GRP, which have a lower roughness coefficient, allow to obtain better results when optimizing of the construction costs. From the hydraulic point of view, these materials help to maximize the filling ration, carrying the design flow with smaller diameters.

The higher maximum filling ratios permits to optimize the flow in the pipes, and therefore minimizes the construction costs. This parameter might always consider the technical recommendations.

The linearization of the non-linear objective function, for the layout selection problem, may use a high number of line segments that describe the original function to have a good precision in the

construction costs estimation. However, the computational time and the capacity of the computer should be considered.

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