COMPARISON BETWEEN DESIGNS OF WDNs PRESENTED IN THE PROJECTS VIABILITY MECHANISM OF THE MVCT AND OPTIMIZED DESIGNS OF THE SAME NETWORKS

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ABSTRACT

Nowadays there are many methodologies to carry out the optimized design of WDNs. However, in Colombia the regulations regarding the water and basic sanitation sector do not demand the application of these methodologies. As a result, new designs of WDNs are generally made following subjective criteria based on the experience of each designer which does not guarantee an optimal use of resources invested in the construction of these networks. This article shows the quantification of the effect that the optimized design would have on the cost and hydraulic parameters of eleven WDNs presented in the Projects Viability Mechanism of the MVCT. With the optimization methodologies used in this research (OPUS and AG) it is found that, for the networks analyzed, the cost of the designs decreases but their resilience deteriorates. Also, the change on cost and resilience caused by optimization methodologies appears to be related to the population and the size of the networks. Based on this, it is necessary that the MVCT establishes guidelines related to the demand for the application of methodologies to optimize WDNs designs and the effect they would have on the cost and resilience of networks.

INTRODUCTION

Improvement of the water and basic sanitation sector has been one of the main objectives of the national development plans of the former governments of Colombia. However, the investment resources are scarce, which limits the execution of projects of this sector. Ministerio de Vivienda, Ciudad y Territorio (MVCT) of Colombia is the institution in charge of the regulation of the water and basic sanitation sector. As part of this regulation, MVCT has implemented a standardized evaluation mechanism exclusive for projects of this sector. This mechanism considers technical, financial, legal, socioeconomic and environmental aspects of every project and determines which projects in the water and basic sanitation sector are viable for implementation using national resources.

The construction of new Drinking Water Distribution Networks (WDNs) in urban and rural areas of Colombia has been part of the actions carried out in search of the improvement of the water and basic sanitation sector. Traditionally, these networks have been designed by trial and error method based on the designer's experience and the restrictions established by the corresponding regulation of this sector. Because this method does not implement any formal economic optimization criteria, WDNs designs in Colombia turn out to be hydraulically feasible as they do not guarantee the minimization of the cost associated with their construction, operation and maintenance. Therefore, this traditional design method does not seem to be effective at addressing the issue associated with the scarcity of investment resources despite the great interest in the construction of WDNs in Colombia. However, today there are many optimization design methodologies that could be applied successfully in the solution of this problem. Cunha & Sousa (1999), Mohan & Babu (2010) and Moosavian & Kasaee Roodsari (2014) are some examples of the existing methodologies for the optimized WDNs design. Additionally, it is important to take into account the artificial intelligence methodologies and the computational advances up to this date allow to consider the optimized design of WDNs as a solved problem, if the cost is the only objective of optimization (Saldarriaga, 2016).

The objective of this research is to quantify the impact that the optimized design methodologies of WDNs would have on cost and resilience of WDNs in Colombia. For this, a sample of new WDNs designs presented in the Projects Viability Mechanism of MVCT are compared with the optimized designs of the same networks considering two design approaches: Optimal Power Use Surface (OPUS) and Genetic Algorithms (AG).

METHODOLOGY

The work carried out in this research required of field work and the use of software. The field work was focused on gathering information about networks presented in the Projects Viability Mechanism. The use of software was necessary to do the optimized designs of the networks. The main steps followed in this research are presented below:

1. Construction of a database with hydraulic and topological information of a sample of the designs of new WDNs presented in the MVCT's Projects Viability Mechanism

To build the database of WDNs designs presented in the MVCT's Projects Viability Mechanism, authorization was requested from this institution to be able to access the information stored in its file. Once the authorization to access the MVCT file was granted, the facilities were visited to consult the available digital information.

Projects in which the objective was the construction of new WDNs and had information concerning topology and hydraulics were of interest. To be included in the database, projects were required to have digital models of the networks with the extension ".inp" that is, models executable with EPANET, in which the material of the pipes, its length, its coefficient of roughness (k_s) or loss (C); location of reservoirs, tanks, pumps and valves, demanded flows and elevation of each node were defined. Additionally, the design reports of the networks included in the database were searched to determine the topological and hydraulic restrictions under which these networks were designed. In addition, the design reports also were sought to know if any optimized design methodology was implemented. The cost and resilience of 11 of these networks have been analyzed. In some cases, it was necessary to make some simplifications on the EPANET models to make possible their modeling during the optimization process. Below is the topology of the networks analyzed in this paper (with the simplification made for their modeling and optimization):

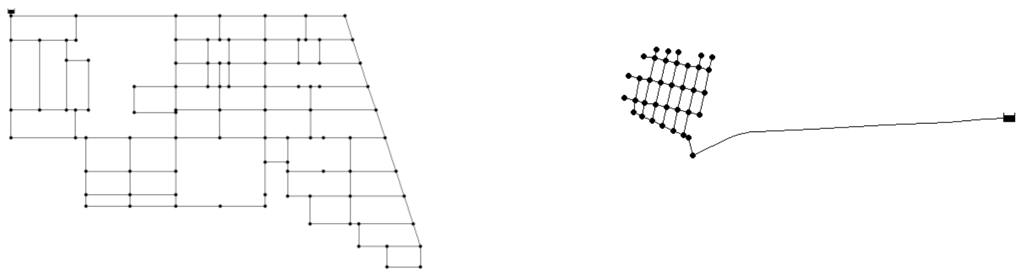

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Figure 1. La Esperanza (1) and La Arenosa (2).

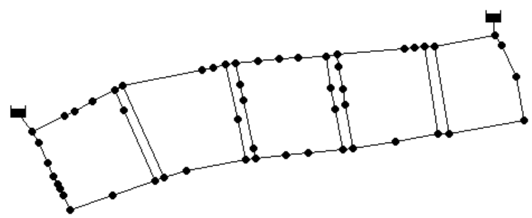

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Figure 2. El Malecón (3).

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Figure 3. Piñuelas (4) and Apulpo (5).

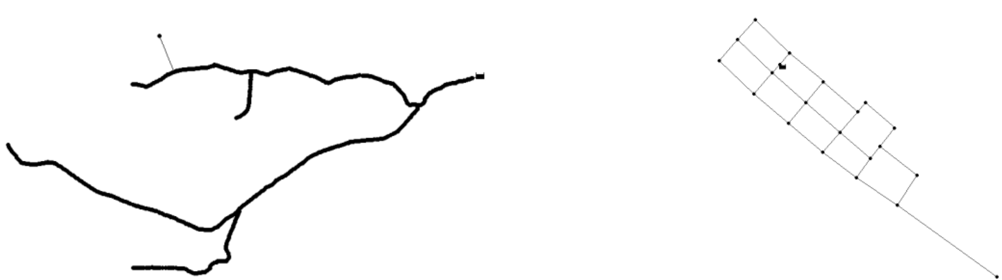

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Figure 4. Arguello Alto y Bajo (6) and Naranjales (7).

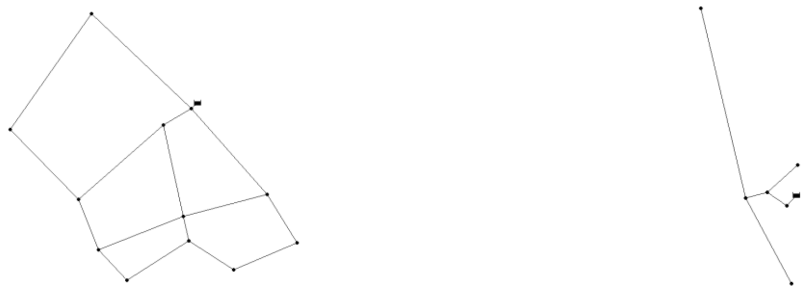

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Figure 5. Puerto Esperanza (8) and Puerto Rico (9).

10 11

Figure 6. San Juan del Soco (10) and San Pedro de Tipisca (11).

2. Selection of cost functions applicable to the networks included in the database

Once the networks database was complete, it was necessary to determine the equations that would allow the estimation of the original design's and the optimized design's cost. The analyzed networks are designed in PVC or HDPE. Therefore, equations were searched to calculate the cost of pipes of such materials. The work of Clark et al. (2002), Marchionni et al. (2016) and Peinado (2016) was consulted. The equations of Peinado (2016) were found to be the most appropriate to be applied in the analysis of the networks of the database. The last since these cost equations are adjusted to information coming from supply and installation cost of pipelines of projects developed in Colombia. The equations of Peinado (2016) applicable to the networks analyzed in this research, their respective ranges of application and their coefficient of determination (CoD) are shown below:

$$C_{PVC\ RDE\ 32.5} = 0.2464D^2 + 557.26D - 36683$$
$$D = (76.2, 609.6)\ mm; CoD = 0.97 \quad (1)$$

$$C_{PVC\ RDE\ 26} = 17.236D^{1.5927}$$
$$D = (50.8, 50)\ mm; CoD = 0.98 \quad (2)$$

$$C_{PVC\ RDE\ 21} = 1.243D^2 + 442.16D - 25926$$
$$D = (50.8, 50)\ mm; CoD = 0.98 \quad (3)$$

$$C_{HDPE\ PN\ 10} = 2.323D^2 + 28.109D + 6392$$
$$D = (63, 500)\ mm; CoD = 0.99 \quad (4)$$

In the previous equations, $C =$ supply and installation unit cost of a pipe (COP/m), $D =$ nominal diameter of a pipe (mm); $CoD =$ coefficient of determination.

3. Optimized design of the networks

The optimized design of the database WDNs was performed with the software REDES, which was developed by the Water Supply and Sewer Systems Research Center (CIACUA) of the Universidad de los Andes. There are five methodologies for the optimized design in the software: Optimal Power Surface Use (OPUS), Optimal Hydraulic Gradient Surface (OHGS), Genetic Algorithms, Harmonic Search and Quick Design (Saldarriaga et al, 2017). The OPUS methodology and Genetic Algorithms were used for the optimized design of the networks. These two methodologies were selected to observe the behavior of the results for methods of different nature. OPUS is based exclusively on hydraulic criteria (Saldarriaga et al., 2010), while genetic algorithms is a stochastic optimization approach (Simpson, Dandy, & Murphy, 1994).

For OPUS and GA, the software REDES allows adjusting the value of the minimum design pressure, the cost function which will be minimized, the list of commercial diameters and the roughness of the material of the pipes, as shown in the window shown below:

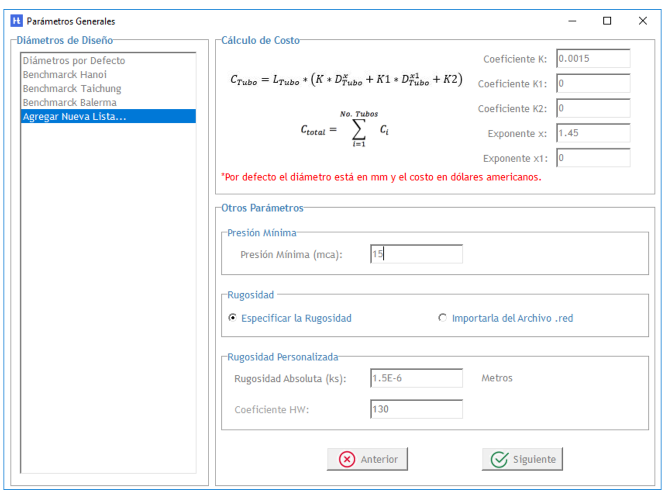

Figure 7. Interface of software REDES for the definition of the design parameters.

The minimum pressure, the roughness of the pipes and the list of commercial diameters for the optimized design are specified based on the information contained in the design reports and the EPANET models of each network. The objective functions were the equations of cost of Peinado (2016) according to each material. In cases where there was more than one material for the pipes of a network, the cost equation of some of the materials considered was used as an objective function. During this research it was observed that the optimization methodologies used do not show sensitivity to the change of the objective function implemented, if these have a polynomial form of three terms or a power form of single term.

4. Analysis of the optimized design impact on the cost and resilience of the networks

The impact on cost caused by the optimized design is estimated calculating the cost of the original networks and optimized networks based on the cost equations selected for each case.

$$C_{Pipes} = \sum_{i=1}^{N} L_i * Cp_i \tag{5}$$

Where: C_{Pipes} = total supply and installation cost of pipes of the network (COP); L_i = length of the i pipe (m); Cp_i = unitary supply and installation cost of the i pipe (COP/m); N = number of pipes in the network $(-)$.

With these results, the percentage difference between the cost corresponding to the network presented in the MVCT and optimized design is estimated. The percentage differences in cost are related to the size of the network, which is expressed in terms of the volume (V) occupied by the network (calculated as the sum of the product between the internal diameter and the length of each pipe). Additionally, a percentage difference normalized by the volume of each network is calculated and related with this volume. Moreover, the percentage difference in cost was related with the population (P) affected by each network. Also, a percentage difference per capita is calculated dividing the percentage difference in cost by the population as show in equation (8). This was related to the population affected by each network.

$$dC = \frac{(C_{Optimized} - C_{MVCT})}{C_{MVCT}} * 100\% \tag{6}$$

$$dCV = \frac{dC}{V} \tag{7}$$

$$dCpc = \frac{dC}{P} \tag{8}$$

Where: dC = percentage differences in cost (%), $dCpc$ = percentage difference per capita of cost $(\%/pop)$; C_{MVCT} = cost of original network present in the Projects Viability Mechanism of the MVCT (COP); $C_{Optimized}$ = cost of network find by methodologies of optimized design (COP).

The analysis of the impact of the optimized designs on the resilience of the networks will be carried out based on the resilience index of Todini (2000). This is a widely used index for quantifying the resilience of WDNs that have a single source of supply. In the software REDES there is a function for the computation of this index. For the analyzed networks in this research, this index can be calculated as follows:

$$I_r = \frac{\sum_{i=1}^{n_n} q_i^*(h_i - h_i^*)}{\sum_{k}^{n_e} Q_k H_k - \sum_{i=1}^{n_n} q_i^* h_i^*} \quad (9)$$

Where: I_r = resilience index of the network $(-)$; q_i^* = flow demand in the i node (m^3/s); h_i^* = minimum head required in each node (m); h_i = head in each node (m); Q_k = flow entering the network from the source k (m^3/s); H_k = head at the source k (m); n_n =number of nodes in the network $(-)$; n_k = number of sources in the network $(-)$.

The percentage difference between the resilience corresponding to the networks presented in the MVCT and optimized designs is estimated. With these results and the information of size and population of the network, the same analysis that was done for the cost is performed.

$$dI_r = \frac{\left(I_{r_{Optimized}} - I_{r_{MVCT}}\right)}{I_{r_{MVCT}}} * 100\% \quad (10)$$

$$dI_rV = \frac{dI_r}{V} \quad (11)$$

$$dI_rpc = \frac{dI_r}{P} \quad (12)$$

Where: dI_r = percentage differences in resilience index (%), dI_rpc = percentage difference per capita of resilience $(\%/pop)$; $I_{r_{MVCT}}$ = resilience index of original network present in the Projects Viability Mechanism of the MVCT (COP); $I_{r_{Optimized}}$ = resilience index of network find by methodologies of optimized design (COP).

RESULTS

In Table 1, information of material, original cost, population, volume of the analyzed networks and resilience is shown:

Table 1. Information of networks analyzed.

Network	Material	Original Cost (COP)	Resilience Index	Population (inhab)	Volume (m3)
La Esperanza	PVC DR 26, 32.5	$ 91,387,120	0.922	3295	521.42
La Arenosa	PEAD PN 10	$ 255,436,593	0.437	6340	509.57
El Malecón	PVC DR 21, 32.5	$ 73,877,613	0.215	9197	244.41
Piñuelas	PEAD PN 10	$ 109,182,084	0.954	1072	331.5
Apulpo	PVC DR 21	$ 8,264,451	0.973	445	49.14
Argüello Alto y Bajo	PVC DR 21, 26 32.5	$ 55,610,343	0.885	1089	421.04
Naranjales	PVC DR 26	$ 23,599,499	0.655	1398	119.3
Puerto Esperanza	PVC DR 26	$ 18,669,418	0.803	1034	109.93
Puerto Rico	PVC DR 26	$ 11,373,032	0.618	531	62.76
San Juan del Soco	PVC DR 26	$ 15,859,497	0.761	671	80.83
San Pedro de Tipisca	PVC DR 21, 26	$ 10,212,548	0.832	489	63.02

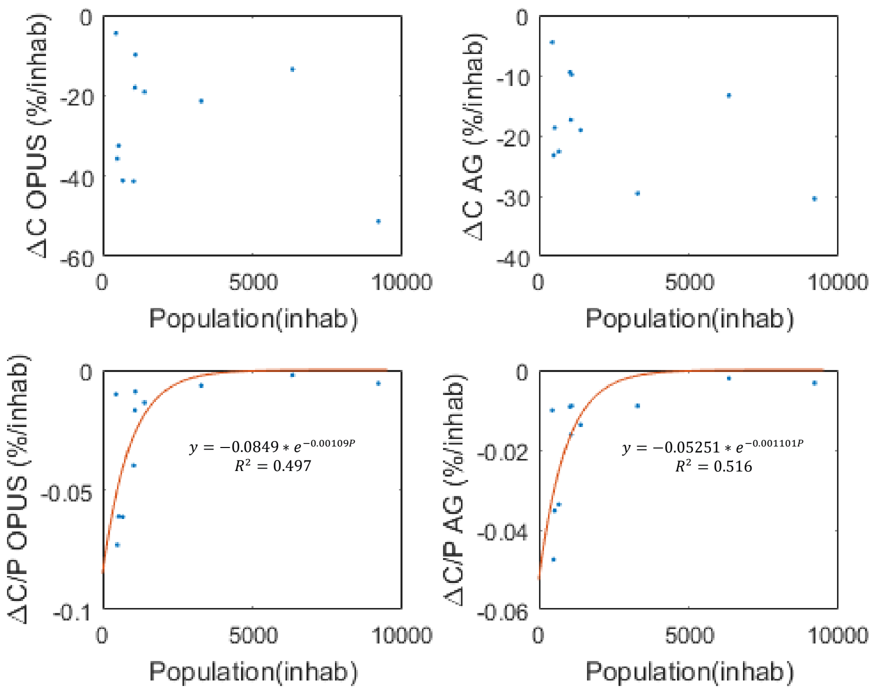

Figure 8. Relation between cost and population.

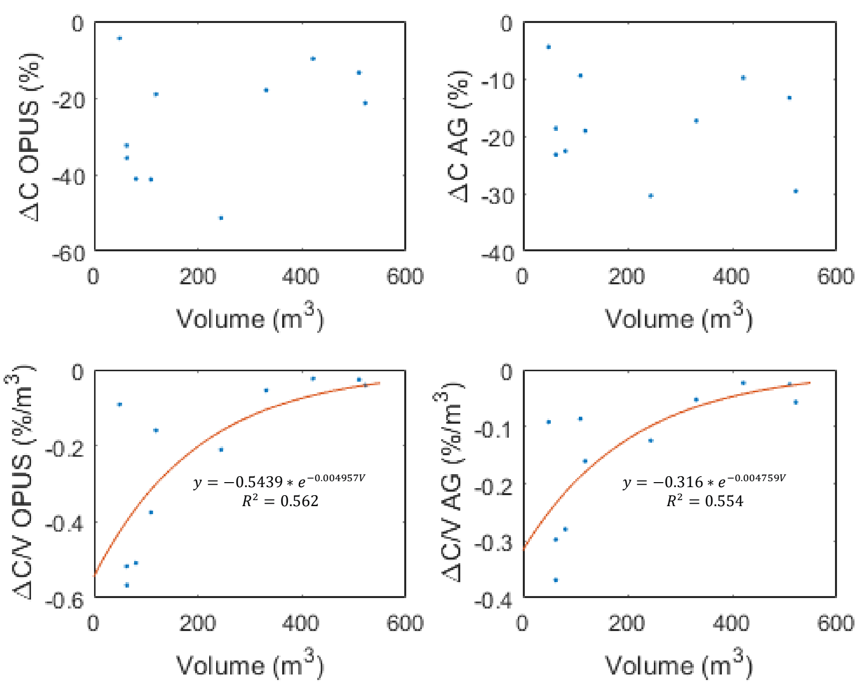

Figure 9. Relation between cost and volume.

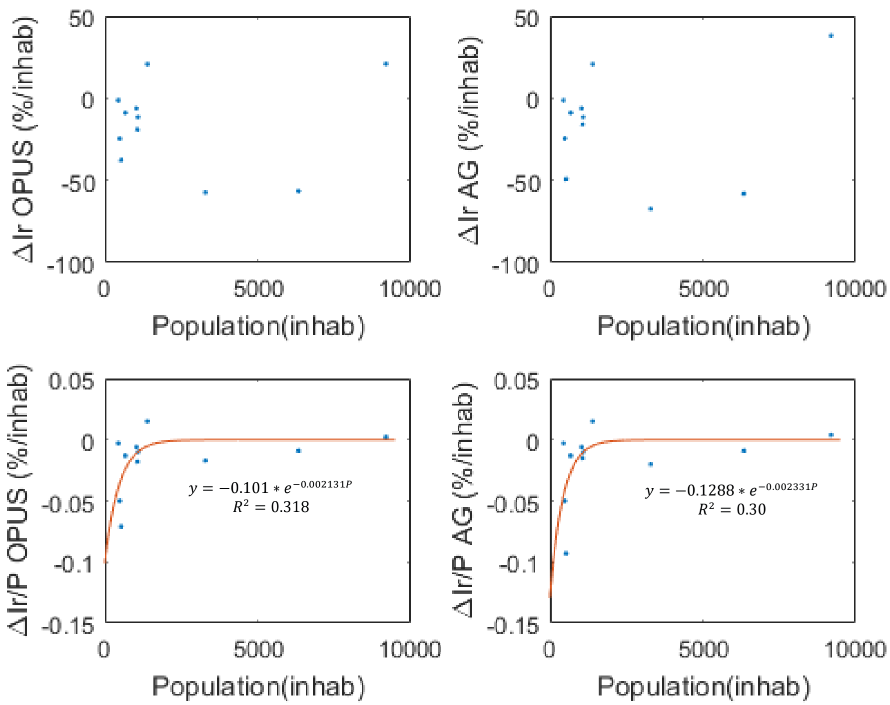

Figure 10. Relation between resilience index and population.

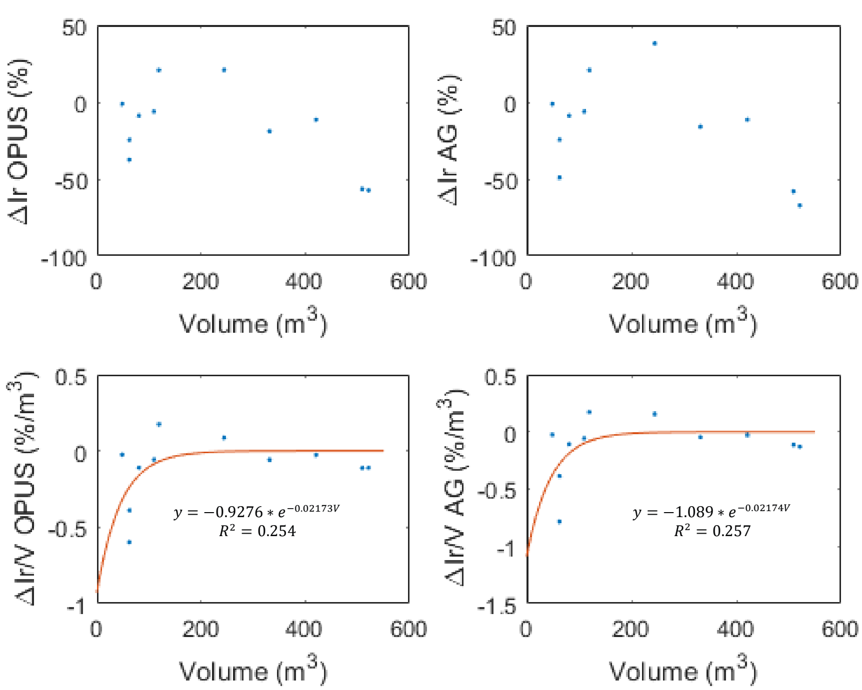

Figure 11. Relation between resilience index and volume.

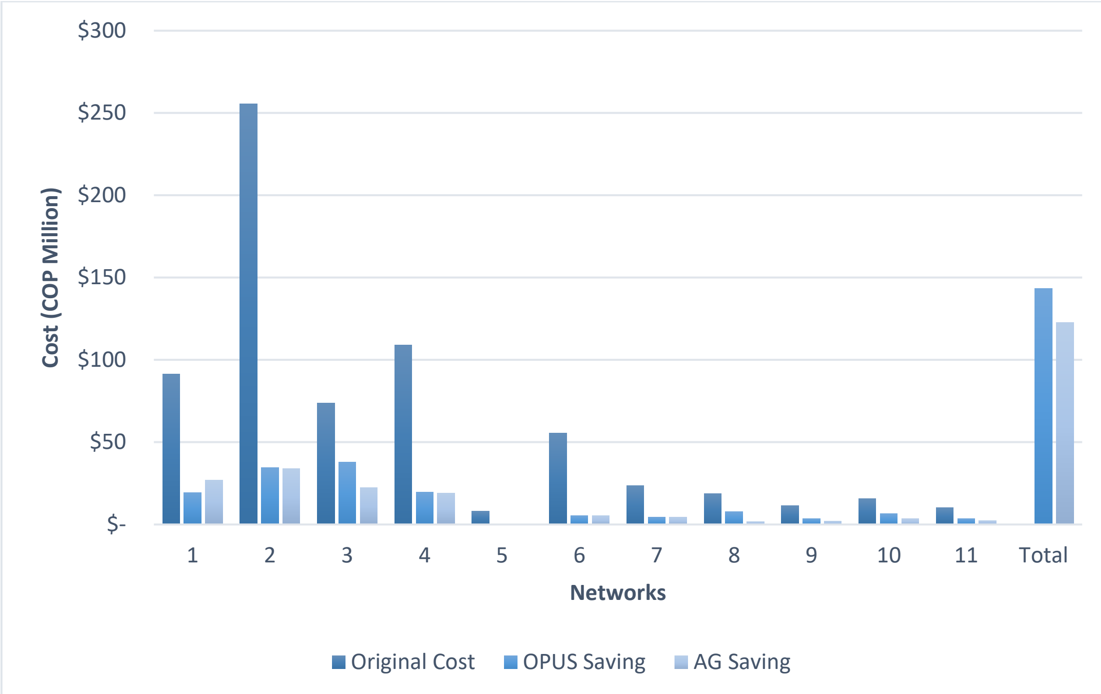

Figure 12. Original cost and saving achieved with optimized design methodologies.

Figure 12 shows the reduction in cost that could be achieved if the OPUS and AG methodology were implemented in the design of the networks analyzed.

CONCLUSIONS

The cost of optimized designs is lower than the cost of the original designs presented in the Projects Viability Mechanism of the MVCT. The total saving achieved is enough to finance the cost of some networks analyzed.

It is observed that reduction of cost and resilience is similar for both OPUS and AG methodologies. This indicates that for the analyzed networks the nature of the methodologies does not matter, this is if they are based on hydraulic criteria or stochastic methods.

It is not possible to identify a clear relationship between percentage reduction of cost and population or volume of the networks analyzed. The same applies to the relationship between resilience of the networks and their population or volume.

The percentage reduction in cost normalized by the population has an exponential relationship with the population. The greater the population, the lower percentage reduction in cost. This means that the larger the population, the lower the impact of the optimized design on the savings per capita. The same relationship was found for the percentage reduction in cost normalized by the size and the size of the networks.

In most cases, the resilience of the network got worse for optimized designs in regard to the original designs presented in the Projects Viability Mechanism. This is explained bearing in mind that design methodologies implemented only consider the cost reduction objective optimization. In order to achieved lower cost, the methodology tends to reduce the diameter of pipes as much as possible. This causes greater friction losses in the pipes, therefore the value of pressure approaches to the minimum pressure allow by the normative at the demand nodes. Which mean that the network becomes more vulnerable to an eventually.

This research must be complemented with the analysis of more designs of new WDNs located in Colombia. Also, this research should be extended to other countries to evaluate the possibility in was appropriate include the demand of methodologies for optimized design of WDNs in the regulation of each country.

It is recommended that the MVCT consider the inclusion of methodologies for the optimized design of WDNs in the regulation of the basic water and sanitation sector in Colombia. This will make it possible to free up economic resources for the construction of more distribution networks. For this the MVCT should invest in complementary research on these issues.

It's recommended to test multicriteria methodologies for optimized designs of WDNs presented in Projects Viability Mechanism and compare their result with the methodologies that only consider the reduction of cost as objective function.

MVCT should include the resilience of the networks as a design parameter of the new WDNs in Colombia.

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