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A Method To Optimize Urban Drainage Networks Based On The Reduction Of The Search Space Of Genetic Algorithms

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Abstract: Based on some biological mechanisms to find solutions Genetic Algorithms demonstrate robustness and efficacy to solve optimization problems. However, one of the problems faced by this type of heuristic is that the efficiency of the algorithm decreases when applied to real-world problems due to the large space that it must explore to find an optimal solution. For this reason, it is necessary to limit the space that the algorithm must explore to the most promising regions. This article presents a methodology to rehabilitate drainage networks with an iterative procedure to reduce the space for searching for solutions. The procedure is based on reducing the initially wide search space to a shortened one that contains the optimal solution. Through iterative processes, the search space is gradually reduced to define the final region that it contains the optimal solution. Once this region is established, a finer discretization is used in the exploration of the space to find the optimal solution. This methodology is applied to a real drainage network that needs to be rehabilitated. The results obtained demonstrate the effectiveness of the process of reducing the space for search solutions to face these types of problems

Keywords: Algorithm; Rehabilitation; Search Space; Urban Drainage; Optimization; Water

1. Introduction

Genetic Algorithms (GAs) are stochastic search strategies based on natural selection mechanisms, which involve aspects of biological evolution to solve optimization problems. One characteristic of these types of algorithms is the way they explore the solution space, while other algorithms follow a single search direction, GAs perform parallel searches in different directions. Another feature in which GAs excel is their ability to explore complex adaptive landscapes. These characteristics have earned the reputation of being robust and effective approaches, and have gained popularity among water resources researchers. In urban drainage network works, GAs have been used in different investigations, among the most representative we have those carried out by Afschar [1], [2], Ciou et al. [3], Park et al. [4], Cimorelli et al. [5], [6] and Abou et al. [7] who used GAs to develop optimal drainage network design methodologies. Despite their frequent use and their advantages, GAs have certain drawbacks. One of those that most worries researchers is the difficulty that GAs can present to find solutions close to the global optimum when they must explore a large search space. This problem is called curse of dimensionality, it refers to the fact that when the Decision Variables (DVs) of a problem increase, the search space grows exponentially. For this reason, the analysis of the search space becomes a task of main importance when working with GAs, this analysis should be able to identify the most promising regions to contain global optimum. Different investigations have been carried out to reduce the search space. One of the first works was carried out by Schraudolph and Belew [8] who presented an approach based on a coding of dynamic parameters to adaptively control the mapping of fixed-length chromosomes to real values, so that in each iteration the algorithm searches in a smaller search space. Later, Ndiritu and Daniell [9] presented an approach to decrease the search space by adaptively controlling the mapping of fixed-length chromosomes to real values, so that, in each subsequent iteration, the algorithm searches a search space smaller. In recent research, Sophocleous et al. [10] present a model to detect and locate leaks in water distribution networks. The model employs two stages, search space reduction and leak detection and location. In the first stage, they reduce the number of DVs and the range of values that they can take, through an analysis of the characteristics of the network. For the second stage they use a genetic algorithm. In parallel, Ngamalieu-Nengoue et al. [11] presented a methodology to reduce the search space for solutions applied to a model of rehabilitation of drainage networks. The reduction of the solution space is based on locating the possible nodes in which tanks will be installed and identifying the possible pipes that should be renewed. These studies demonstrate the growing interest in improving the performance of optimization models. Consequently, the objective of this work is to present a method for the optimization of urban drainage networks that contemplates the reduction of the space for seeking solutions. The method significantly reduces computational effort and improves efficiency in the search for the global optimum. To demonstrate the benefits of the method it is applied in the E-chicó network, this network was used by other researchers in previous works.

2. Methods

2.1. The optimization model

The optimization model of this article was presented in a previous work [12] The model has been tested and has proven its worth in solving these types of problems. It includes replacing pipes, installing Storm Tanks (STs), and installing Hydraulic Controls (HCs). The model uses as optimization engine a modified GA called Pseudo Genetic Algorithm (PGA) that changes the binary coding of the chromosome for integer coding, this change has the advantage that each gene represents a DV that in optimization of hydraulic problems gives good results [13] this algorithm is connected to the Storm Water Management Model (SWMM) [14] by a toolkit [15]. The objective of the model is to minimize the Objective Function (OF) evaluated to find the most economically advantageous solution that allows reducing the impact of flooding in the urban environment. Thus proposed the model, the possible diameters of the pipes to be renewed, the storage volume of the STs and the degrees of opening of the HC are defined as DVs. Each of these DVs can take a discrete value within a options list to be analyzed by the GA. The pipes used in drainage networks generally have normalized diameters so they are discrete variables per se, this does not happen with the volume of the STs and the opening of the HC that must be discretized. Concerning the volume of STs, the model considers the current height of the manholes as the maximum height of the tank, leaving the area as a variable. To discretize the area of the tank, the maximum area available for its construction is defined and divided into a certain number of sections. For HC the degree of opening of the element can take a continuous range of values. To discretize these values, degrees of opening are defined that vary from the fully open position to a maximum closed position. Transforming the search space from continuous to discrete inherently leads to a problem. If the discretization is small, that is, the number of options that the DV can take are reduced, the exploration of the space may not be effective, and may not reach identify an optimal solution. Differently, if the discretization is highly refined, the options list that the DV can take would significantly increase in size, causing the search space to grow exponentially and the computational effort required to be considerable. It is then necessary to define a options list that guarantees that the exploration is efficient. In this method, two types of options lists are defined, one called coarse and the other much more refined called fine.

The optimization problem aims to minimize the costs associated with flood damage as little investment as possible. According to this, an OF is established that evaluates the problem in economic terms. The first term corresponds to the cost of the renewal of pipes that must be replaced due to lack of capacity. This function is established from actual cost data provided by pipe manufacturers. The function that relates the unit cost of the pipelines with their diameter has been adjusted.

$$C_D(D_i) = \left(40.69\, D_i + 208.06\, {D_i}^2\right) L_i \tag{1}$$

In Equation (1), Di is the diameter of the pipe, Li is the length of the pipe, the coefficients 40.69 and 208.06 are specific adjustment coefficients for the analyzed network. The second term corresponds to the cost of installing ST that would be required to temporarily store water that the network is not capable of dislodging in an event of extreme rain.

$$C_V(V_i) = 16\,923 + 318.40\ V_i^{0,65} \quad (2)$$

The first term of Equation (2) represents a minimum cost established for the ST while the second term is variable as a function of the required storage volume (Vi) affected by a constant 318.40 and an exponent 0.65. The third term of the OF represents the cost of the installation of HCs at the outlet of certain STs, established from data of real costs of gate valves.

$$C_v(D_i) = 4.17\ D_i - 0.000211\ D_i^{\,2} \quad (3)$$

In Equation (3), Di is the diameter of the pipe, 4.14 and 0.000211 are specific adjustment coefficients for the analyzed network. Finally, an equation must be defined that presents the cost of flood damage, this function depends on the level reached by the water yi. The definition of this cost is based on the work carried out by Ngamalieu-Nengoue et al. [17] these authors crossed this curve with the costs of flooding per square meter for different land uses. In equation (4) from a certain level y_{max} the damage is considered irreparable and therefore the function stops growing and the cost will reach its maximum C_{max}. For the network analyze, the defined parameters of the equation are as follows y_{max}= 1.40, C_{max} =1 268, λ=-4.99, r = 2.

$$C_y(y_i) = C_{max}\left(1 - e^{-\lambda \frac{y_i}{y_{max}}}\right)^{r} \quad (4)$$

In this way, the objective function shown in equation (5) is defined.

$$F = \sum_{i=1}^{n} C_D(D_i) + \tau_2 \sum_{i=1}^{n} C_V(V_i) + \tau_3 \sum_{i=1}^{n} C_v\,(D_i) + \tau_4 \sum_{i=1}^{n} C_y(y_i) \quad (5)$$

2.2. Search space reduction

The process of reducing the search space for solutions is as follows:

1. As a first step, a first mapping of the entire search space of the algorithm is carried out, each DV is analyzed by the algorithm using a options list with a coarse discretization. The use of a coarse options list allows identifying fast the DVs that may be included in the most promising region of the algorithm's exploration space. After performing a certain number of evaluations, the 5th Percentile (P_5) of these evaluations is analyzed, the candidate DVs to the new search region are selected through a selection criterion based on the repeatability.
2. The process is repeated in the new defined region, eliminating the DVs that do not meet the selection criteria. In each iteration of the process, the convergence of the results towards certain DVs that's repeatability in the sampling increases, defining each time the region with the best solutions.
3. The process ends when all DVs meet the selection criteria and the search space cannot be further reduced.
4. Once the final search region is defined, the final optimization is performed in this new scenario. In this new optimization the refined options list is used. In order to carry out a much more detailed exploration of the search space in order to identify the global optimum of the problem.

2.3. Application of the model

The methodology was applied to a sector of the drainage network of the city of Bogotá, Colombia (Figure 1). This network called E-Chico is made up of 35 hydrological sub-basins that occupy a surface area of 51 hectares, 35 conduits and 35 connection nodes. The ducts are circular in section with diameters ranging from 300 mm to 1 400 mm. And they cover a length of approximately 5 000 meters. The network works completely under gravity. For the analysis, a design storm was used based on an Intensity-Duration-Frequency curve previously defined by Ngamalieu-Nengoue et al. [16] calculated using the alternate blocks method with 5-minute intervals.

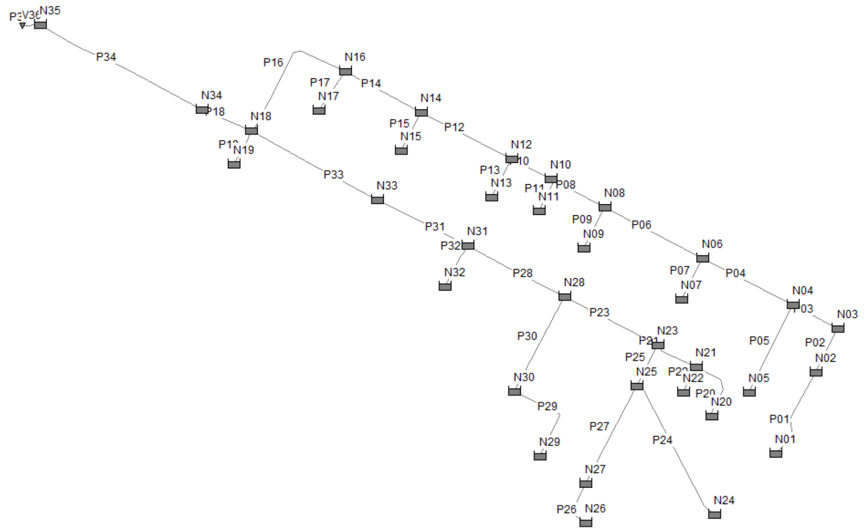

Figure 1. E-Chicó urban drainage network.

3. Results

As the first step of the method, the mapping of the total search space is carried out. Figure (2) shows the results of the applied method in the entire search space. The result of the P_5 shows that certain DV present a higher repeatability. By applying the selection criteria, the areas of the search space less interesting to explore are eliminated, thus defining a new search space. Applying the method iteratively reduces the definition of smaller regions until the final search region is defined. Figure (3) shows the final search space.

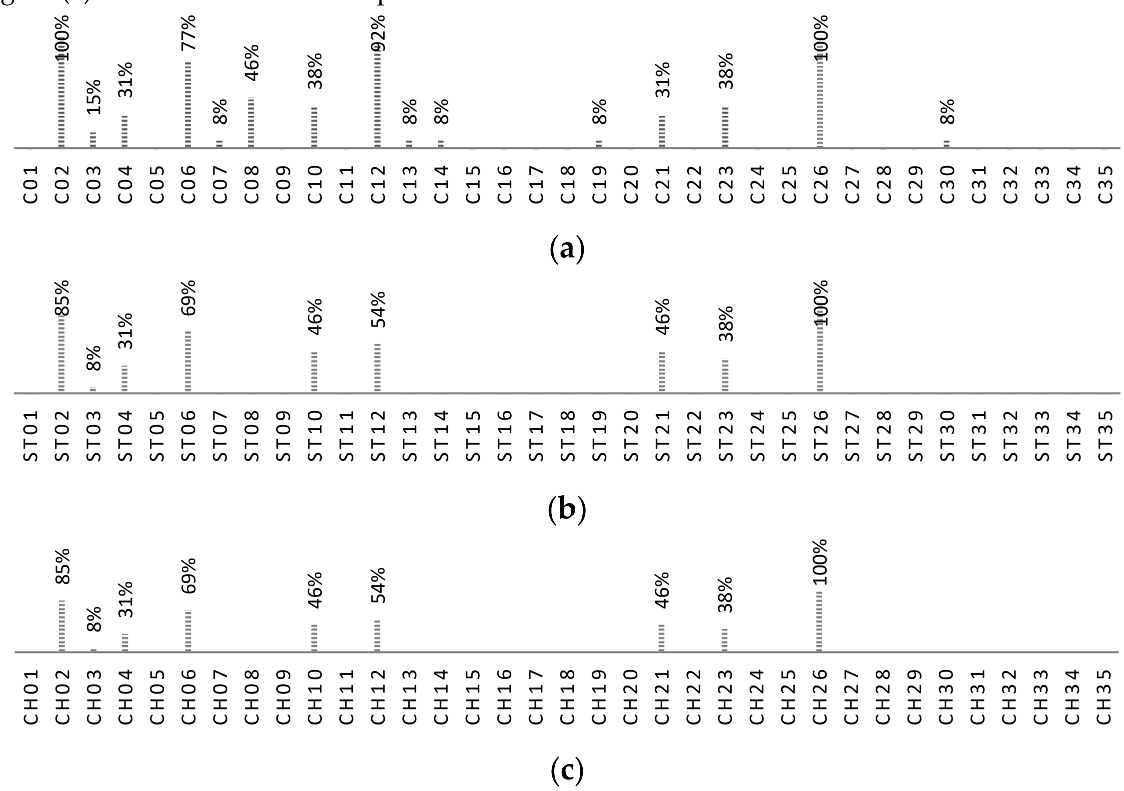

Figure 2. Results of applying the methodology in the search space. (a) results of the pipelines. (b) Results of the STs. (c) Results of the CH.

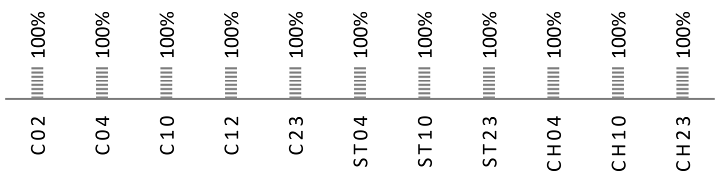

Figure 3. Final search space of the E-chicó network.

Once the search space has been reduced, we proceed to the final optimization of the network. The results show a reduction in the OF when compared with a previous study carried out on the same network. Table 1 shows the costs of each term. It should be noted that flood damage decreases in the proposed solution. Specifically, the network requires the renewal of a pipe (C02), the installation of the STs (ST04, ST10, ST23) and the installation of HC elements at their outlet (CH04, CH10, CH23).

Table 1. Comparison of results in previous research and the proposed method.

Method	F.O.	Pipe cost	ST cost	HC cost	Flood Damage cost
Bayas-Jiménez et al. 2019 [12]	209,150.40 €	11,130.70 €	188,957.79 €	-	9,061.91 €
Proposed	199,713.95 €	6,583.81 €	179,757.68 €	7,671.75 €	5,700.66 €

4. Discussion

The use of a reduced options list in the search space reduction stage is a valid alternative to carry out a rough exploration of the search space in order to identify the region that contains the best solutions. The inclusion of a HC in the optimization model significantly improves the results obtained. In larger networks, an interesting alternative the parallel application of the methodology in different sectors of the network with the aim of narrowing down the search space based on the network topology.

Future research on this topic should include the study of the optimal size of the options list in the discretization of the search space, especially in networks of considerable proportions. Likewise, the study of the algorithm parameters must be considered to improve the overall efficiency of the model. Finally, the method is interesting for its application with other heuristic approaches.

Author Contributions: All authors contributed extensively to the work presented in this paper.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

MDPI: Multidisciplinary Digital Publishing Institute
DOAJ: Directory of open access journals
GA: Genetic Algorithm
PGA: Pseudo Genetic Agorithm
DV: Decisission Variable
OF: Objective Function
ST: Storm Tank
HC: Hydraulic Control
SWMM: Storm Water Management Model

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