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AN OPTIMIZATION MODEL FOR PRIORITIZING SEWERAGE MAINTENANCE SCHEDULING

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ABSTRACT

Water utility companies, responsible for providing water supply and sewerage services to the urban population, are constantly seeking to improve their service. In the case of sewer systems, effective scheduling of preventive maintenance of urban water infrastructure has been identified as an important activity in order to reduce costs and protect the integrity of citizens and the surrounding, both built and natural, environments. Consequently, with particular focus on Bogotá (Colombia), we developed an optimization model that generates a preventive maintenance plan on a set of zones within the city. These zones have in common a high failure probability over a defined time period due to sediment-related blockages. The mixed integer optimization model implemented here, considers a multi-objective function that maximizes the protection of the city. For the maximization process we take into account the entities that would be affected in case of flooding (i.e. health centers, education centers, market places) caused by a sediment-related sewer system blockage. The information about the entities is analyzed through Geographic Information Systems (GIS) and Analytic Hierarchy Process (AHP). Furthermore, the model satisfies budget and operational capacity restrictions, due to their finite nature. Based on a model sensitivity analysis, we can conclude that the ratio between preventive and corrective maintenance costs is critical to define a proactive maintenance schedule, while other parameters such as the available budget are not. Making a comparison of the methodology currently used by the local water utility and our model, the latter obtained better results in terms of city protection and budget and resources allocation.

INTRODUCTION

Sewer systems are a fundamental part for a city that should operate without interruptions [1]. Malfunctioning sewers involve health risks [2], property damage and traffic problems, which affect the inhabitants of the urban area. Solids in wastewater can induce blockages in the sewer network, decreasing the discharge capacity. This may cause higher flood risks and frequent overflow spills [3]. Due to their limited accessibility and complexity, maintenance and rehabilitation plans of large sewer networks must be addressed carefully in order to optimize the cost and resources used.

Traditionally, sewer system failures have been approached in a reactive way [4], however a preventive strategy is frequently more cost-effective [5]. In spite of this, proactive schemes are hindered by difficulties in monitoring and a lack of data [6] [7] [3]. A structured decision-making process is required in order to assist this problem and materialize a prioritized maintenance plan [1].

Focusing on sediment-related blockages, there are two main ways of assessing future failures in a sewer system: hydraulic and statistical models. Hydraulic models, aim at representing water flow and sediment transport physical mechanisms. For example Peñalver *et al*. [8] implemented a physical based sediment transport model in order to establish a maintenance schedule. Other contributions in this area are for example Ji [9] and Fraser *et al.* [10]. However, describing sewer system hydraulic and transport process is a challenging task and requires detailed information [11]. On the other hand, statistical analysis of recorded failure events has been successfully used. For instance Rodriguez *et al.* [3] developed a statistical model that uses a customer complaints database covering the 7.5 million inhabitants of Bogotá (Colombia). This information was useful to estimate blockage rate distributions and thus a prioritized maintenance plan.

Statistical and probabilistic models are usually applied along with optimization techniques. In terms of sewer system applications, rehabilitation plans have been approached with evolutionary algorithms [12], genetic algorithms [13], [1] [4] and Pareto curve [6]. In particular, Mohamed *et al*. [4] worked with Markov Chains Model for sewer network deterioration modeling and subsequently applied a multi-objective model to optimize the tradeoff between cost of rehabilitation, life cycle, and condition of the system. In spite of this, all of them have only been applied to rehabilitation plans instead of a proactive maintenance plan.

This paper proposes an adaptation of a mixed integer optimization model developed by Medaglia *et al*. [14] which is useful in a scenario with a set of investment projects to be chosen. Additionally, each project has a time frame to be executed and there are costs and benefits linked with its selection. The objective is to establish an investment schedule in order to maximize a particular objective function. In this research, the model includes a set of zones in Bogotá with a high probability of failure in the sewer network. This information is obtained from the model developed by Rodriguez *et al*. [3]. Furthermore each zone has its own characteristics such as sediment-related blockage rate, population density, and city infrastructure (i.e. health and education centers, market places and government institutions). The main purpose of the model is to define a preventive maintenance plan over a defined time period. This plan selects the zones that must be maintained in order to maximize the protection of the city from flooding events. In order to properly describe the city infrastructure, GIS applications are used. Moreover the model includes restrictions, such as budget available and maintenance resources.

METHODS AND MODEL

The optimization model includes a set of city zones C that are prone to failing during the time horizon T. Additionally there is a set of different structures E that could fail inside each zone (i.e. manholes, gully pots and pipes). Proactive and reactive maintenance schemes are considered in A. A set of performance measures M considers the entities that would be at risk if a flooding event occurs (i.e. hospitals, major roads, public entities, fire stations, police stations, market places, homes, education centers and industries). Finally a set of renewable R and non-renewable NR resources is also included.

The duration of the maintenance of the zone $i \in C$, under the scheme $j \in A$ in the type of structure $e \in E$, is considered in $v_{i,j,e}$. Moreover there is a time frame where maintenance is possible ($t^{-}_{i,j,e}$, $t^{+}_{i,j,e}$). Preventive maintenance can only be executed before the failure date of a zone.

The budget considered at time t is represented as p_t . The cost associated with the maintenance of a zone i, under the scheme j, in the structure e is defined as $c_{i,j,e}$. The demand of the resource r to intervene in the zone i, under the scheme j, in the structure e, during the period of time k ($k \in \{0, \dots, v_{i,j,e} - 1\}$) is represented by $u_{i,j,e,k,r}$. Furthermore the availability of the resource r in the time t is $d_{r,t}$. Finally, the benefit to maintain under the scheme j, the structure e of the zone i, following the performance measure m is defined as $I_{i,j,e,m}$. The relative importance of each performance measure m is λ_m.

The model identifies which zones should be maintained and how (i.e. proactive or corrective). Additionally it selects the structure on which the procedure must be focused and the time to do it. The binary variable $y_{i,j,e,t}$ takes the value of 1 if the maintenance of the zone i, under the scheme j, in the structure e starts at time t, and it takes the value of 0, otherwise. The model requires an auxiliary binary variable $x_{i,j,e,t,k}$ that takes the value of 1 if the period of time k($k \in \{0, \dots, v_{i,j,e} - 1\}$) in the maintenance of the zone i, under the scheme j, in the structure e is assigned to the time t in the planning horizon$\{t^{-}_{i,j,e}, \dots, \min\{t^{+}_{i,j,e}, T - v_{i,j,e} + 1\}\}$, and it takes the value of 0, otherwise. Finally the budget is contained in the variable $r_t (\geq 0)$, $t \in \{1, \dots, T\}$. The proposed mixed integer program is as follows. The objective function (1), maximizes the total protection of the city.

$$\max. \sum_{i \epsilon C} \sum_{j \epsilon A} \sum_{e \epsilon E} \sum_{m \epsilon M} \sum_{t=t_{i,j,e}^{-}}^{min\{t_{i,j,e}^{+}, T - v_{i,j,e}+1\}} \lambda_m \cdot I_{i,j,e,m} \cdot y_{i,j,e,t} \quad (1)$$

subject to

$$\sum_{j \in A} \sum_{t=t_{i,j,e}^{-}}^{min\{t_{i,j,e}^{+}, T - v_{i,j,e}+1\}} y_{i,j,e,t} \leq 1 \quad i \in C, e \in E \quad (2)$$

$$y_{i,j,e,t} = x_{i,j,e,t+k,k} \quad i \in C, j \in A, e \in E, k \in \{0, \dots, v_{i,j,e} - 1\}, \quad t \in \left\{t_{i,j,e}^{-}, .., min\{t_{i,j,e}^{+}, T - v_{i,j,e} + 1\}\right\} \quad (3)$$

$$r_{t+1} = r_t + p_t - \sum_{i \in C} \sum_{j \in A} \sum_{e \in E} c_{i,j,e} \cdot y_{i,j,e,t} \quad t \in \{0, \dots, T\} \quad (4)$$

$$\textstyle\sum_{i \in C} \sum_{j \in a} \sum_{e \in E} \sum_{k=0}^{v_{i,j,e}-1} x_{i,j,e,t,k} \cdot u_{i,j,e,k,r} \leq d_{r,t} \quad r \in R, t \in \{0, \dots, T\} \quad (5)$$

$$r_t \geq 0 \quad t \in \{0, \dots, T\} \quad (6)$$

$$y_{i,j,e,t} \in \{0,1\} \quad i \in C, j \in A, e \in E, t \in \left\{t_{i,j,e}^{-}, .., min\{t_{i,j,e}^{+}, T - v_{i,j,e} + 1\}\right\} \quad (7)$$

$$x_{i,j,e,t,k} \in \{0,1\} \quad i \in C, j \in A, e \in E, k \in \{0, \dots, v_{i,j,e} - 1\}, t \in \{t_{i,j,e}^{-}, .., t_{i,j,e}^{+} + v_{i,j,e} - 1\} \quad (8)$$

As is it shown in (1), the model maximizes the protection of the city by selecting the zones with more infrastructures at risk. The set of restrictions in (2) assures that one zone can only be maintained one time and under only one scheme. In (3) variable x and variable y are related in order to coordinate starting periods with maintenance periods. The restrictions in (4) and (5) regulate the budget and the resources available for each period. Finally in (6) and (7) the allowable values for the decision variables are restricted.

The optimization model requires the use of three different sources of input data: (a) the results from the statistical model developed by Rodriguez *et al.* [3], which provides $v_{i,j,e}$ and ($t^{-}_{i,j,e}$, $t^{+}_{i,j,e}$), (b) resource availability, demand of equipments for maintenance and operational costs.($d_{r,t}, u_{i,j,e,k,r}, p_t, c_{i,j,e}$) and (c) geographical information describing the infrastructure of the city (i.e. hospitals, major roads, public entities, fire stations, police stations, market places, homes, education centers and industries). Particularly, GIS techniques are implemented in order to analyze this geographical information. Thus, knowing the quantity for each type of entity contained in every zone of the city will be useful to determine the value of $I_{i,j,e,m}$. Moreover, to include the relative importance between the different types of entities, an Analytic Hierarchy Process is implemented [15]. Therefore the model contemplates, for example, the relative importance of a hospital over a market place, in terms of general health, infrastructure protection, operational congestion, and social benefits (λ_m).

The model was implemented for the Bogotá's sewer system, which is divided into five operational districts for the purpose of sewage management. These districts are further split into a total of 24,392 grid squares of about 0.03 km^2. For each square, which is called a zone in this paper, characteristics such as the number of manholes and gully pots, pipe length, slope and blockage rate are known.

RESULTS AND DISCUSSION

Executing the statistical model proposed by Rodriguez *et al.* [3] for April 2013, 590 zones had a high probability of failure in the District # 2 of Bogotá. Considering the Bogotá's precipitation regimen, April is one of the months with maximum precipitation per year. Additionally the results from Guzmán [16], indicate that the month of April has been historically one of the periods with higher reports of failures in the sewer system. This District # 2 of the city is the fourth in terms of the number of users. Additionally it covers 103.5 km^2, includes a third of the city pipe length, and has been the objective of previous studies due to its high receptivity to improvements. The objective of the optimization model was to decide which zones, out of the 590, should be maintained, under what scheme (preventive or corrective), when (day), and what structure (manhole, gully pot or pipe).

Currently, Bogotá's water and sewer public utility, Empresa de Alcantarillado y Acueducto de Bogotá (EAAB), carries a preventive maintenance plan, which consists of a monthly selection of 10 zones to maintain, based exclusively on failure rates and system conditions. Comparing the model results with the strategy used by EAAB, see Table 1, the former increases the objective function by 7.57 times. This responds to the fact that the model decided to prevent 58 zones instead of 10. However, analyzing the records of the failures that indeed happened in this month, EAAB plan would have protected 3 zones instead of the 23 predicted by the model. This means an improvement of 9.7% in the effectiveness of the preventative plan. Extending the analysis to all the districts in the city, Figure 1 illustrates that the model improves the maintenance plan in the Districts #2 and #3. On the other hand, District #1, #4 and #5 do not meet the criteria to be properly approached by the optimization model due to the limited number of zones with high failure probability during the time frame. Sensibility analyses were carried out in order to understand the model behavior when the model assumptions are modified: a) operational requirements analysis, b) preventive maintenance cost and c) budget availability. Obtained results are presented and discussed below.

Table 1. Model performance Vs. EAAB

Version	Objective Function	Number of selected zones for the preventive plan	Protected zones	Effectiveness	Plan Cost ($ US)
EAAB	1.054E-05	10	3	**30.0%**	$ 46,440
Model	7.977E-05	58	23	**39.7%**	$ 45,540
Relation	**7.57**	**5.8**	**-**	**-**	**-**

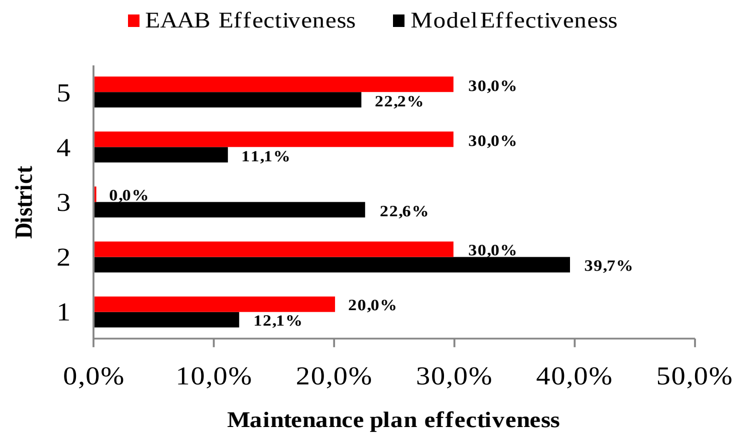

Figure 1. Maintenance plan effectiveness for all the Districts.

a) Operational requirements analysis.

Maintenance of a sewer system usually requires four different resources: vactor sewer cleaners, vehicles equipped with rods, dump trucks and, vehicles equipped with winchers. However not all the failures in the system require all the equipment, and the time of usage is different in each case. That is why, only when the supervisor identifies the cause and the magnitude of the blockage, the operational requirements are defined. According to this phenomenon, a sensibility analysis is implemented, changing the model parameter of percentage of time that each resource is used. Explicitly, 30 iterations were executed randomly changing this parameter. Stability in the obtained results behavior indicates that no more instances were required.

In Figure 2 the results of the sensitivity analysis are presented for District # 2. Figure 2a, illustrates the number of zones, which even when their demand for resources consumption is changed through alterations in the percentage of time that each resource is used, they should always be maintained. In this case, over the 590 zones, the model in almost all the iterations selected to correctively maintain the same 297 zones. On the other hand, preventive maintenance was consistent in the same 46 zones through all the iterations. In a more general scheme, Figure 2b shows how regardless if it is a preventive or corrective scheme, the same 60% of the 590 zones is maintained in almost all the iterations.

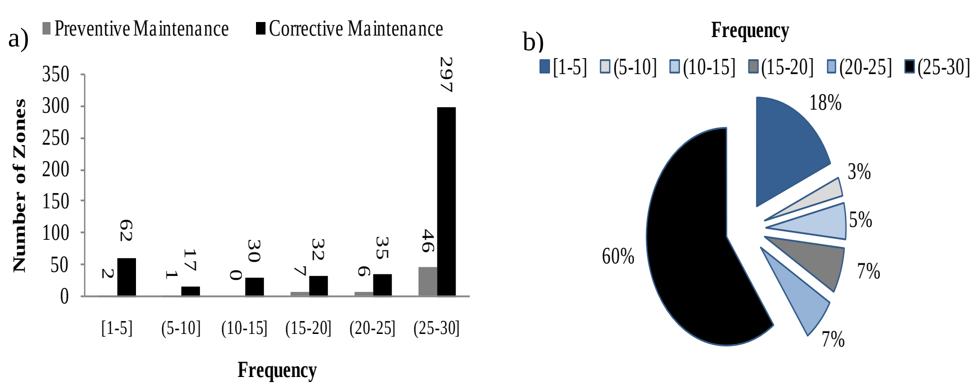

Figure 2. Operational requirements sensibility. a) Intervention scheme discriminated. b) Unified frequencies

The results of this sensibility analysis exemplify that in spite of the amount of consumed resources, a group of zones should always be maintained. This is beneficial, taking into account the uncertainty of the equipment requirements presented above.

b) Preventive maintenance cost sensibility.

As discussed by Fenner [5] preventive maintenance is more cost-effective than a reactive scheme. In spite of this, detailed information about the preventive maintenance cost has not been recorded by the EAAB. In order to overcome the lack of information, the preventive maintenance cost was defined as a percentage of the corrective maintenance cost. This instead is reported periodically by the EAAB. Furthermore, the model has been iterative executed changing this percentage (ranging from 0 to 100%) and an analysis for District # 2 is presented in Figure 3. Besides this, two measures are analyzed: the objective function and the relation between the numbers of preventive maintenance interventions over the numbers of corrective maintenance interventions. It can be observed that once the percentage of the corrective maintenance cost grows, then the objective function decreases. This is supported by the fact that preventive maintenance has more influence in the objective function improving the protection of the city. Moreover, if the percentage is less than 30%, the model suggests to preventively maintain all the possible zones (the ones that are prone to failure during the time frame). On the other hand, if the percentage is more than 30%, the benefit of maintaining a zone under a preventive scheme is not equivalent with the preventive maintenance cost. This situation leads to a decrease in the amount of preventive maintenance. Extending the analysis, 40% and 35% were found as the breakpoint percentages for the Districts #1 and #3. On the contrary, no percentage was found for the Districts #4 and #5 due to the limited number of zones with high failure probability during the time frame.Overall any increase in maintenance costs reduces the value of the objective function.

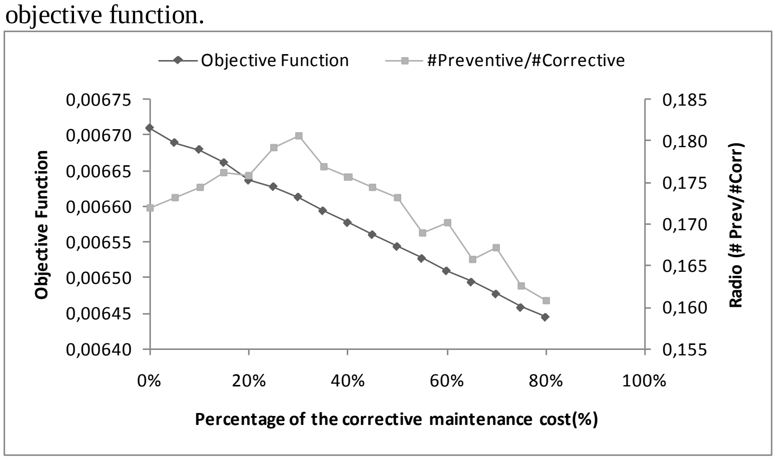

Figure 3. Preventive maintenance cost sensibility.

c) Budget availability sensibility.

The EAAB monthly establishes fixed budget to be used to maintenance plans. In this analysis the budget available is increased to illustrate the model sensibility to this parameter. An increment in the budget will increase the value of the objective function. Consequently, more zones could be preventively or correctively maintained. Nevertheless, Figure 4 shows how the extra budget is not always directed to preventive interventions. Even though preventive maintenance is less expensive, to preventively maintain some city zones do not generate an important change in the objective function. As a result, the extra budget is directed to corrective maintenance.

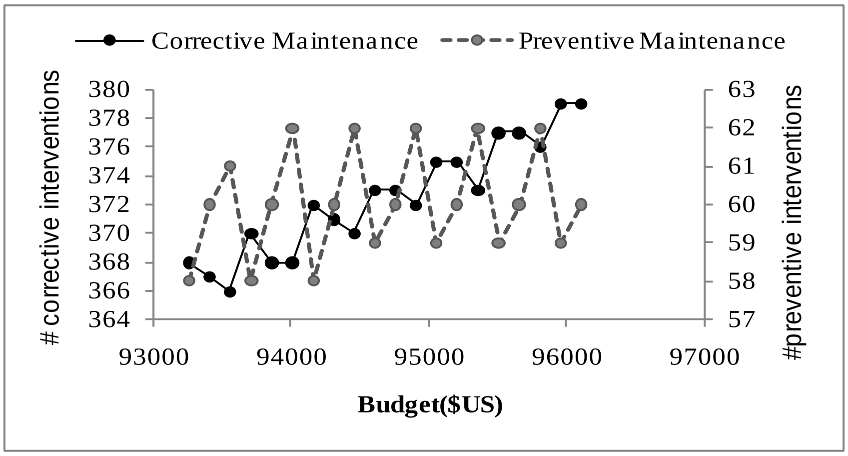

Figure 4.Maintenance plan in response to changes in the budget.

CONCLUSION

Summarizing the study presented in this document, a multi-objective optimization model was developed in order to establish a preventive maintenance plan for the Bogotá's sewer network. The goal was to prioritize the maintenance on a set of zones with high failure probability due to sediment-related blockage. The model identifies which zones of the city should be maintained, the maintenance scheme (preventive or corrective), the specific structure within the zone (manhole, gully pot, pipe) to be maintained and the starting time to do it. The model maximizes the protection of the city in terms of the entities that would be affected in case of flooding (i.e. hospitals, major roads, public entities, fire stations, police stations, market places, homes, education centers and industries). Additionally the model satisfies budget and operational resource restrictions. Moreover, engineering tools such as Geographical Information Systems and Analytic Hierarchy Process are implemented in order to acquire the appropriate parameters to run the model.

The model was executed for Abril 2013 using the results of the statistical model presented by Rodríguez *et al.* [3] for Bogotá in the EAAB operative District # 2. Additionally, the case study enabled some model sensibility analyses. These illustrated the parameters that should be took considered when this kind of applications are developed. For the case of operational resources, changes in the percentage of time that each resource is needed, directly affects the model solution. However, multiple iterations showed that in spite of the uncertainty of consumed resources, some zones of the city should always be maintained. On the other hand, alterations in the preventive maintenance cost, substantially changes the model results. Some efforts are required to properly define this parameter. Finally, increases in the budget availability do not modify the preventive maintenance plan, otherwise the extra budget is placed in corrective maintenances.

In order to improve the model scope, proper recording of preventive and corrective maintenance costs is recommended. Additional precedence restrictions could be added: in this case, a specific zone could be only maintained if another one has been already intervened. This restriction could reflect the real transportation behavior of the wastewater through the city. As a final point, this model could be also implemented in rehabilitation plans and not only in maintenance plans.

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