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Influencing Factors for Scheduling Optimal Pipeline Replacement with Budgetary Constraints

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Abstract. We propose an instrument to aid in the decision-making process that allows for the prioritization of needs for the water distribution network renewal planning and to identify these priorities applying the methodology Multicriteria Decision Support Systems (MDSS) and Genetic Algorithms. We consider the various influencing factors involved in decision-making. The instrument developed proposes an acceptable sequence of interventions in the water network, identifying the hierarchy of the groups of pipes before renovation work beings and takes into account all factors associated with the endogenous and exogenous factors and the technical constraints of functioning of the water network for a given planning horizon.

Keywords: *Water distribution network, renewal, hierarchy, decision-making.*

1 INTRODUCTION

Identifing the factors that influence the determination for prioritization in the renewal of the pipes is not an easy task, given that the selection should support the fundamental criteria at the time the pipe is considered for renewal. Age is undoubtedly the first criterion for inclusion in the list, but not the only one. Coupled with age is the availability of financial resources required and the financial resources available to water companies that operate water distribution networks. The aim is to improve the reliability and operation of the network. The emphasis on the renewal of the pipes is done according to a decision-making process that takes into account a number of variables related to the pipes and their environment, the conditions of operation of the network, technical restrictions and of course the financial implications.

2 OBJECTIVES AND SCOPE

The main objective is to study the factors of influence on the deteriorating pipes, in order to propose a model for the scheduling of work on the prioritization of the renewal of pipelines. We take into consideration a number of factors in order to prioritize of a group of pipes with similar characteristics including age and type of material. We also consider the annual budget amounts available for the rehabilitation of pipelines. This requires the development of the proposed methodology for the allocation of priorities for renewal of pipes, using the system to support the decision making of the weighted sums, detailing the weighting matrix of alternatives and evaluation of results. Once addressed the methodology referred, it was applied the method of weighted sums for the prioritization of renewal in eight groups of piping within the water distribution network in Celaya City, Mexico, where the grouping of partial scores of each pipe is made with respect to each of the criteria obtained as a result of prioritizing the group of pipes. The results of sensitivity analysis are applied before changes in the consideration of the values on weights of the criteria. Finally we apply the method for ranking each of the groups of pipes for each factor considered applying Genetic Algorithm.

3 ELECTION OF THE CRITERIA

The selection of criteria that can really influence in the decision to replace or not to replace a pipe or to position it on a priority list is not immediate. This is undoubtedly a particular decision of the managers of each network. They must choose the criteria more representative in their environment and make an assessment in accord with the reality they live, depending of course, on their technical expertise of the business. Based on the above, here is the classification of the eight criteria that in the view of the network manager in Celaya City deserved to be considered. The criteria are classified into groups with different characteristics, but they allow for a quantitative assessment of the item analysis. They are the “Fundamental” group , “Hydraulic” group and the “Specials” group.

3.1 Fundamental criteria

The age of the pipe.- A network updates its status by changing its parameters, not just physical (the most important: internal diameter and roughness), but also hydraulics, both to adapt to new conditions imposed by the quality of water, and as a result of variations in changes in the demands occurring by the growth of the population served, bring with them a degree of inevitable ageing. Thus, the aging is natural and predictable to a certain extent, and thus should be valued.

History of each pipe breakage. -Here we evaluate the number and frequency of breaks that occurred over a period of time, that arise as a result not only of the age of the pipe, but also other factors that make two pipes with the same age have different ratios in occurrence of leak.

3.2 Hydraulic criteria

Transport capacity of each pipe.- Based on the theoretical flow of the pipeline, both in its state of "new pipeline", as in the current state (with some reduction in diameter) one calculates the loss of hydraulic capacity as the difference between the transport capacity "new" and transport capacity "today”.

Index deficiency nodes.- The index reflects the impact of the unavailability of a pipeline in water supply to subscribers. Allows censoring all the consumer nodes where the supply is not assured (Wagner et al, 1988). We assume that under a certain pressure P_{low} the water supply is not assured. For each pipe "cut" there is a calculation of the pressure with the help of EPANET[1] ®, and we can then perform a comparison with the pressure P_{low}. The lowest threshold allowed for Celaya City is 10 mwc.,

Impact flow escaped by the behavior of the network, compared with an optimal level of efficiency.- It is a fact that in any water distribution system an unknown amount of water that is lost. This "uncontrolled" water is not lost through only leakage (although mostly), but is also due to other causes such as measurement errors and consumption not measured and / or unauthorized.

[1] Developed by EPA's (U.S.A) Water Supply and Water Resources Division, EPANET is software that models water distribution piping systems, EPANET is public domain software that may be freely used.

3.3 Special criteria

Optimal time to replace the pipe according to Shamir-Howard.- This approach considers the balance between the cost to repairs breaks and the cost of replacing the pipe, which, with the passage of time increases the occurrence of breaks.

Repairing all the breaks increases the cost of maintaining each pipe over time.
That rate increases to the point when it is economically more profitable to replace the pipes rather than continue with the repetitive process of repetitive “unoperability-repair-operability”. Based on the theory presented by Shamir and Howard (Shamir and al, 1979) you find the optimal year of renewal, Being penalized pipe that has a renewal date earliest, from the reference year.

Influence of a water “cut” in different types of users of the water distribution network.- Subscribers directly connected to the pipe cut will have no water, while the others suffer the effects of lower water pressure, at various periods of time (from a few hours to a few days). It is therefore the intent of this section to quantify these effects before cutting service in the sector by closing the flow in each of the pipes studied especially the number of users considered "major" by the water company “JUMAPA”.

Impact of a break in the environment.- The assessments about the importance of the traffic disruptions caused, by the disruption of the working hours of the affected community, are carried out using qualifications type as "strong", "moderate", "weak" and "extreme". There are, however, other effects that are more precisely quantifiable: economic damages above and below commercial premises, replacing the pavement, among others. It is thus a little more natural to think of the possibility of assigning numerical weights to each of these qualification types than was previously possible. Figure 1 shows the outline of the hydraulic model of the water distribution network on one of the sectors which corresponds to downtown.

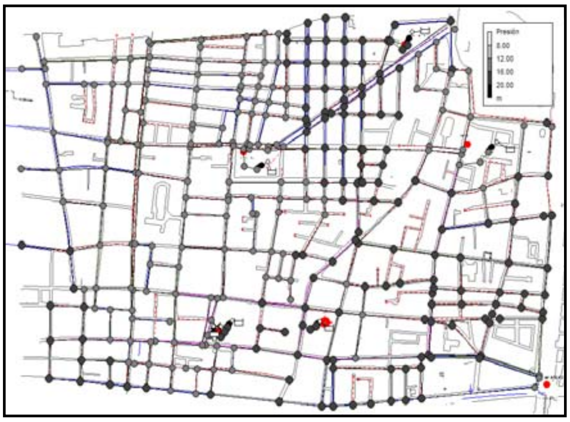

Figure 1. Outline hydraulic model

4 EVALUATION OF PIPES SELECTED ACCORDING TO THE CRITERIA DEFINED.

It comes with mathematical calculation that allows you to obtain a rating for each criterion of the eight groups of pipes on the same scale. Once the introduction of the selected criteria is realized, then you can evaluate the current status of the water network in the city of Celaya.

4.1 Fundamental criteria

The age of the pipe.- Is proposed a maximum value of 10 points for a pipe 50 years old and a minimum of 0 in the case of a new pipe (0 years). The rating associated with each age, as expressed in the equation 1 has been made assuming a parabolic relationship between the two ends. It seems logical to penalize in an increasingly proportionate way to the age of the pipe.

$$Value\,(age) = 10 \cdot \left(\frac{t}{60}\right)^2 \qquad (1)$$

Table 1. Factor values

Pipe ID	Lenght m	Age	Number of breaks (breaks/ Km. year)	Interpo-lation
AC 1	12605	40	4.09	10.00
AC 2	7243	30	3.77	9.18
Fo Fo 1	11613	50	3.44	8.36
Fo Ga 1	8600	50	3.79	9.24
Fo Ga 2	7540	40	4.06	9.92
PVC30	25201	30	2.81	6.77
PVC20	11548	20	3.00	7.25
Polythene	13865	10	3.73	9.09

History of each pipe breakage.- The number of breakages is proportional to the length of the pipe, for this reason the number of breaks is estimated per km., and the year of each pipe as a fundamental value to calculate the penalty (table 1). The values of breaking/ Km. and year are high, but for various reasons are considered high. We propose a linear interpolation where we assign a value of 10 to the maximum number of breakages and assigned a value 0 for the minimum number of breakage per km per year (Hirner, 1997).

4.2 Hydraulic criteria

Transport capacity of each pipe.- In this first hydraulic criterion it is desired to value the hydraulic capacity of the pipe regardless of their behavior and real possibilities in the network. Knowning both the pipes diameter and roughness characteristics, and that the roughness of the pipe increases with the passage of time as well as other features such as type of material, conducted water flow quality, etc. it decides the absolute roughness for a given moment of time through the following equation.

$$k_{si}(t) = k_{soi} + a_i(t + g_i) \quad (2)$$

Moreover, the actual diameter of the pipe for a given moment in time is calculated by the equation:

$$D_i(t) = D_{oi}(1 - red_i(t + g_i)) \quad (3)$$

With the formulation taken from the previous model posed by Sharp and Walski (1998) one can determine the operation of a water distribution network for a given period of time considering the increased roughness of the pipe and obstruction by the same inlay of materials, both linear with respect to time. Based on the above we can calculate the pressure loss per km. of pipe anytime, through a simulation model using EPANET ®.

Index deficiency nodes.- This procedure makes it possible to identify the group of affected nodes. Once these nodes are identified, one calculates each pipe cut and prepares the report between the number of non-communicating nodes and the total number of nodes that make up the network. There will be a penalty for the number of pipes that are below the lowest pressure allowed. The penalty was higher when the number of larger pipes fell below the minimum allowable pressure. The sector that had the highest number of "important" pipelines had the greatest penalty. Is assigned a value of 10 for the largest IDN and 0 for the lowest index, which is directly proportional to the value of the IDN. The evaluation was carried out through the expression 4:

$$IDN_j = \frac{Number\ nodes_{low}}{Total\ \ number\ nodes} \quad (4)$$

Impact flow escaped by the behavior of the network, compared with an optimal level of efficiency.- This approach influences the consumption of the affected nodes, in addition to the changes incurred in the pipe nodes analyzed where we had the leak. When comparing the simulation of EPANET ® with the 85% efficiency of rating of the physical network, it was considered a satisfactory ratio (AWWA Water Leak Detection and Accountability Committee, 2004).Comparing the simulation results with current actual data. The allocation of leakage is dependent on pressure, the same happens with the 85% efficiency level where the escaped flow in each node is based on the pressure. The evaluation was conducted using the following expression.

$$IIQ_{leak} = \frac{Num.nodes_{lowreal} - Num.nodes_{low85\%}}{Total\ number\ nodes} \quad (5)$$

The score will be the greater value derived from the equation 5 for each group of pipe assigned the value of 10 and for the lower the value of zero, making an interpolation for the intermediate values.

4.3 Special criteria

Optimal time to replace the pipe according to Shamir-Howard..- The statistical methodology proposed here gathers pipes that have the same properties that are considered discriminatory: age (years) and size (diameter). Other factors such as corrosion, material, the method of union between pipes, the conditions of the bed of the pipe, and traffic are considered fairly homogeneous for all pipes in every sector of the Celaya network. Using a linear regression "age-size" we obtained for each group, the relationship between the number of breaks and time. For this type of analysis, Shamir and Howard (1979) proposed for the temporary development of breakages per unit length an exponential law as reflected in the following equation, where N (t) is the number of breaks / km in the year (t) and (t_0) represents the reference year.

$$N(t)_i = N(t_o)_i * e^{A_i(t+g_i)} \quad (6)$$

$N(t)_i$ is the number of breakages per unit length per year in pipe in time t (km^{-1}, $year^{-1}$), $N(t_0)_i$ is the $N(t)_i$ in the year of installation of the pipe (new pipe); t is the time in years; g_i is the age of the pipe in the present (years), and A_i is the ratio of the rate of growth of breakages in the pipe (years). Shamir and Howard (1979) derive an expression (7) to calculate the optimal timing of replacement of a pipe (t_s), adding the cost of replacing the pipe (C_s) and the costs of repair (C_r) occurred in the period t_s– t_0 and derive regarding t_s year to obtain the replacement year at the minimum cost. In the following equation the variable (*i*) represents the annual rate of inflation and (t_o) the reference year.

$$t_s = -g_i + \frac{1}{A_i}\ln\left[\frac{C_s + \ln(1+i)}{C_r N(t_o)}\right] \quad (7)$$

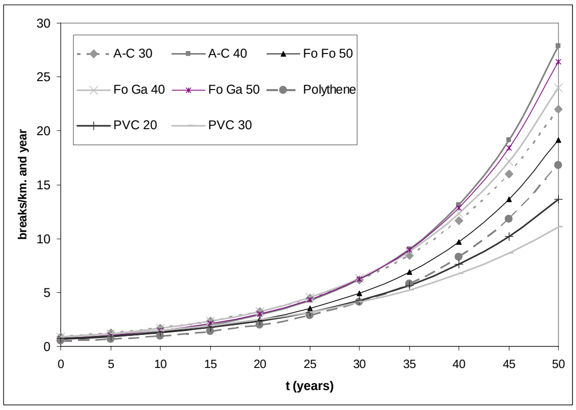

Figure 2. Prediction of breaks in the time

Now is the time to evaluate this approach. No penalty is given for pipes that have a year of optimal renewal greater than or equal to 25 years, but a penalty of 10 points is given to a value of ts - tc = 0 years, considering that the most recent pipes 20-30 years old are made with better materials except polyethylene with not very specific characteristics since its installation. the values about the prediction of breaks in the time are shown in figure. 2.

Influence of a water "cut" in different types of user in the water distribution network:.- We had considered using the JUMAPA classification for consumers called "majors" which are users who consume at least 100m^3 monthly. In the simulated program EPANET ® (EPA, 2000) we cut each pipe by initiating main pipes at the network and analyze the number of affected nodes (at 09:00 h) when the greatest demand occurs. and the degree of influence of this court in each node, By we also measured the original pressure drop, as well as the number of affected nodes are located where the major consumers are located. Results are shown in figure 3.

	Demand	Closed pipelines 13	23	33	19	21	Closed pipelines 13	23	33	19	21
ID Node	>100						Presión m	Presión m	Presión m	Presión m	Presión m
node 1	0	no	no	no	no	no	6.75	0.00	12.32	14.72	14.79
node 2	0	no	no	no	no	no	6.74	0.00	12.49	14.76	14.82
node 3	0	no	no	no	no	no	6.64	0.00	12.97	14.84	14.89
node 4	0	no	no	no	no	no	6.84	0.00	13.42	15.13	15.17
node 5	0	no	no	no	no	no	6.85	0.00	13.63	15.21	15.25
node 6	0	no	no	no	no	no	7.47	0.00	11.82	15.09	15.17
node 7	0	no	no	no	no	no	7.08	0.00	11.11	14.57	14.66
node 8	100	si	si	no	no	no	8.32	0.00	11.04	15.07	15.16
node 9	100	si	si	no	no	no	8.47	0.00	11.13	15.17	15.26
node 10	0	no	no	no	no	no	16.38	0.00	15.78	16.28	16.3
node 11	100	no	si	si	si	si	12.87	7.52	0.00	0.00	0.00
node 12	0	no	no	no	no	no	12.46	7.14	0.00	0.00	0.00
node 13	100	no	si	si	si	no	13.83	8.69	0.00	0.00	15.29
node 14	0	no	no	no	no	no	14.04	9.06	0.00	0.00	14.9
Max	**4**	**2**	**4**	**2**	**2**	**1**	**9**	**22**	**12**	**12**	**9**
		0.5	**1**	**0.5**	**0.5**	**0.25**	**0.41**	**1.00**	**0.55**	**0.55**	**0.41**
		0.91	2.00	1.05	1.05	0.66					
Average	**5.66**	**4.55**	**10.00**	**5.23**	**5.23**	**3.30**					

Figure 3. Concentrate and scoring result in closure of pipeline

Impact of a break in the environment.- This factor will be the score with a valuation of 10 for a density of extreme traffic, 6 for a strong density, 3 in the case of a moderate density and 0 for a low density of traffic. A relative weight of 60% is considered for each of the 4 factors analysed. The same set of values is applied to the density of buildings and / or historic monuments, obtaining the score of each pipe.

5 METHODOLOGY

Method for prioritization pipelines renewal using-Decision Support System of the weighted sums.

5.1 Matrix weighing alternatives

Of the different approaches used to generate the set of efficient solutions, this was the first to develop. Zadeh in 1963 was the one who suggested this method. Its basic idea is to combine all the criteria in a unique role. To that end, you associate a weight or ratio of consideration to each criterion, at which time you add the value of an alternative to each criterion (adjusting these by the weights of these criteria), to generate and achieve a global solution of this alternative. Each alternative depending on the criteria evaluated, reaches a (V_{AJ}) valuation, which is affected by the weight assigned to this criterion, (W_{CrI}). Having said that, and given a set of criteria m and n alternatives, the alternative J will add m products as (V_{AJ} * W_{CrI}) represented in a summation. The matrix includes n amounts for n alternative as shown in figure 4.

	Criterion 1 (weight 1)	Criterion.. (weight ...)	Crietrion m (weight m)	Final sum of every alternative ↓
Alternative 1 ↓ (Valuation 1)	$V_{A1}*W_{Cr1}$	$V_{A1}*W_{Cr...}$	$V_{A1}*W_{Crm}$ →	$\Sigma (V_{A1}*C_j)$
Alternative..... ↓ (Valuation ....)	$V_{A...}*W_{Cr1}$	$V_{A...}*W_{Cr...}$	$V_{A...}*W_{Crm}$ →	$\Sigma (V_{A...}*C_j)$
Alternative n ↓ (Valuation n)	$V_{An}*W_{Cr1}$	$V_{An}*W_{Cr...}$	$V_{An}*W_{Crm}$ →	$\Sigma (V_{A1}*C_j)$

Figure 4. Typical structure of the matrix weighting alternatives

Priority 1	Aj :	Σfinal Aj >	Σfinal An >	Σfinal A...>	Σfinal Ai
Priority 2	An :	Σfinal An >	Σfinal A...>	Σfinal Ai	
Priority...	A...:	Σfinal A.. >	Σfinal Ai		
Priority n	Aj :				

Figure 5. Prioritization of alternatives depending on the value of the sum end of each

5.2 Assessment final results

Table 2. Order of prioritize on 100

Order of prioritize	Assessment on 100	Hierarchy
1	7.33	FoGa (C1)
2	6.71	FoGa (C2)
3	6.62	FoFo (C1)
4	6.11	AC(A1)
5	5.39	AC(A2)
6	4.80	PVC20
7	4.52	Polythene
8	4.48	PVC30

In the specific case of keeping a list of prioritized pipes ready to renew with greater urgency, given that the evaluation of each criterion implies greater need to renew when the score is higher in each case, we immediately conclude that greater sum of these products involves a greater need, and at the global level, to renew the pipe which is associated with the product. As a result, the final step in the process is to organize, from highest to lowest, each of the final results achieved by the alternatives (see figure 5), in order to know the final order for renewal.

Implementation of the decision support system about weighted amounts for prioritization renewal in eight groups pipelines network Celaya City, Mexico .- We need to make some clarifications regarding the composition of the water distribution network on the diameters referred to on the majority of the pipes that make up the network, which range between 75 mm and 200 mm. The age of the pipes in the downtown sector are older (50 years) and there are different materials in the five areas such as: Fo-Fo, Fo-Ga, PVC and polyethylene. The eight groups of pipes selected were homogeneous in terms of the type of material and age.

Association of partial ratings of each pipe with respect to each of the criteria considered .- Once you evaluate the pipes for each criterion and all receive a value qualifier between 0 and 10 for each criterion, it is time to add these values, and average the weight of each criterion as described in the matrix above to achieve a final outcome for each alternative, which allows you to establish as a last step, the order of priority for renewal. Finally partial and weighted scoring of each pipe, is shown in table 2. Once you get the prioritization of the group of pipes, we first have to galvanized iron pipes that are 50 years old, followed by galvanized iron pipes 40 years old, which are older than the cast iron pipes FoFo (C1). The same is true for PVC pipes which are younger but are higher priority on this list. (i.e. PVC piping 20 years old get ratings higher than those pipes PVC30 in hydraulic and fundamental criteria.) Another significant data obtained are the very close values between the following pipes in the downtown sector: FoGa (C2) FoFo (C1), AC (A1) except the Asbestos Cement pipes AC (A2). This tells us what the homogeneous characteristics are in terms of the age and the material, and furthermore, their behaviour so far. Proof of this is the hydraulic behavior.

Table 3. Result of the sensibility analysis

Order of prioritize	Assessment on 100	Hierarchy
1	7.36	Fo Ga (C1)
2	7.07	FoFo (C1)
3	6.67	Fo Ga (C2)
4	6.11	AC (A1)
5	4.71	AC (A2)
6	4.00	PVC30
7	3.74	PVC20
8	3.54	Polythene

Sensitivity analysis of the results to changes in the consideration of the values on weights the criteria.- If the relative weight in the key considerations were interspersed values, (i.e. were rated 30% age and 20% at breakage history (original values were 20% age, 30% breakage history), another change is QII_{break} from 10% to 5%, and the special criteria that was rated at 10% optimal renewal, is now 5%. The system after these changes is reflected in table 3. Clearly, the first group of pipes to be considered for renewal is the group that corresponds to the galvanized iron pipes (FoGa 1). With the two assessments that have been made, we note that the prioritization changes considerably by changing the weight the ratings. Therefore it is important to conduct a deeper analysis of the next group of pipes to be considered for

Table 4 Assessment and scoring result of factors influence

FACTORS INFLUENCE										
ASSESSMENT	50		35			15				
	20	30	15	10	10	5	5	5		
Pipe ID	Age	Brekage history	Hydraulic capacity	NDR	QII_{break}	Times of replace	Influence break Q	Sorrounding impact		
AC 1	6,40	10,00	3,98	4,1	0	7,19	3,26	6	2	10,00
AC 2	3,60	9,19	4,64	5,8	2,45	0	3,04	4,8	7	3,04
Fo Fo 1	10,00	8,36	5,02	5,2	0,55	6,33	4,46	4,8	1	10,00
Fo Ga 1	10,00	9,25	4,73	4,6	4,62	3,85	4,57	10	8	10,00
Fo Ga 2	6,40	9,92	4,1	5,5	3,72	10	4,1	4,2	6	10,00
PVC30	3,60	6,78	4,92	3,6	3,24	0	0,12	6	3	4,92
PVC20	1,60	7,26	4,27	5,5	10	0	2,27	0	5	10,00
Polythene	0,40	9,10	2,86	10	2,23	0	1,12	0	4	10,00
										67,96

renewal, based on the factors set forth, define the pipe which has more impact on each factor individually. Based on the above, propose a method for ranking each of the groups of pipes for each factor considered, using genetic algorithms through the Evolver program. The results are shown in table 4.

6 CONCLUSIONS

Managers who make decisions on prioritization for the renewal of the pipes have a complicated task, because there are several factors of influence involved. For this reason, we believe that the method developed here can be a good tool for decision making in its simplicity. The results obtained in this study show us that the first group of pipelines on the prioritization is the group of pipe FoGa1 even with the sensitivity analysis. We note that this group of pipes score highest with established methods of scoring, Given that the factors for groups of the “fundamental” and “hydraulic” criteria obtained high values for both because of their characteristics of age and the number of breaks by the length, there is no doubt that it is the first group of pipes that should be considered for renewal. For the second and third place we will support the results of indexing and base the decision on the criteria JUMAPA decides.

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Information about the Evolver program can be found online: http://www.palisade/educational/evolver/.