SCHEDULING WATER NETWORKS RENEWAL USING HYBRID OPTIMIZATION MODEL

Amir Nafi[1], Caty Werey[2], and Patrick Llerena[3]

ABSTRACT

Through a bibliography review of works treating of renewal and rehabilitation of water distribution network, we identified a set of variables and factors that should be taken into account along the decision process. The approach proposed aims to schedule works on the network according to financial resources assess, considering variables linked with the environment of pipes and factors describing the whole network trough its hydraulic performance. Using Genetic Algorithm and Hydraulic simulation, the model proposes an acceptable policy, defining sequences of works on the water network. Four decisions are possible at the pipe scale: to do nothing (to repair if break occurs), to rehabilitate, to replace and to reinforce. The decisions taken enhance reliability of water distribution network and gives better satisfaction to consumers.

KEY WORDS

Water network, Scheduling, Multi-objective, Optimization, Genetic algorithm, Hydraulic simulation, Renewal.

INTRODUCTION

Water utilities are dealing with problems relative to water quality, leaks, loss of pressure in pipes, interruptions of distribution and contamination of water. Those problems can be described by factors linked with the state of pipes itself and the environment that brings deterioration of networks. If so, the water utility has to prevent occurrence of failures and lack of water by an adequate renewal policy. The aim of our work is to propose a decision tool trough an optimization model considering damages prediction on pipes taking into account technical, economical and financial constraints. The decision process proposed is based on forecasting pipes failures using a statistical model, Proportional Hazard Model (PHM) that predicts failures occurrence using endogenous and exogenous variables. The forecast of failures allows assessing the futures expenditures supported by the water utility

[1] Phd Student, Joint research unit in Public Utilities Management, 1 quai koch, BP61039 F-67070 Strasbourg, France, Phone:+33 3/88248293, FAX:+33 3/88248284, anafi@engees.u-strasbg.fr.

[2] Research Engineer, Joint research unit in Public Utilities Management, 1 quai koch, BP61039 F-67070 Strasbourg, France,Phone:+33 3/88248253,FAX: +33 3/88248284, cwerey@engees.u-strasbg.fr.

[3] Professor in Economics, Director of BETA(Bureau d'Economie Théorique et Appliquée), Joint research unit ULP-CNRS n° 7522, 61 Avenue de la Forêt Noire 67070 Strasbourg, France, Phone :+33 3/90242184, FAX :+33 3/90242070 ,pllerena@cournot.u-strasbg.fr.

using an adequate objective function. We consider a set of four alternatives: to do nothing (repair if break), to rehabilitate, to replace and to reinforce. Possible policies are coded and assessed by Genetic Algorithm and hydraulic simulation ensured by Epanet2®. An adequate evaluation of the importance of each pipe in the network is defined by the Hydraulic Critical Index, that describes the impact of deficiency of a given pipe on the whole network. Calculation is done using Excel® macro in VBA and Epanet Toolkit. The approach takes into account constraints linked with the hydraulic performance of network translated by residual pressure and demand on nodes, also budget constraints which describes the available resources. Using a multi-objective approach, the model proposes acceptable renewal policies along a time horizon, defining sequences of works on the network according to financial resources available.

PROBLEM STATEMENTS

Maintenance policy of water network is widely treated in bibliography, depending on criteria and approach used in making decision process. We identify methods based on the description of failures occurrences by statistical model that allow predicting damages on pipes using historical data considering past breaks on network. We can describe the different states of pipe using Markov chains. The deterioration of pipes is considered as a Markov process described by a set of states. The process is irreversible and the evolution from one state to an other is described by transition probability. The distinction between degradation states is not easy to establish and the analysis of deterioration of buried pipe is impossible. Markov chain description is more used for bridges and roads. Eisenbeis (1996) describes failures occurrences using Proportional Hazard Model proposed by Andreou (1986), which supposes that the time between breaks is described helping with a Weibull function. The model takes into account variables linked to the pipe itself and its environment. The impact of these variables on the pipe deterioration process is translated by covariates. Model aims to predict pipe state given a set of variables. Werey (2000) proposes scheduling of replacement on pipes using model PHM to assess failure probabilities involved in an objective function, taking into account social costs, related to a break on network. Two alternatives are considered, to repair if break occurs or to replace pipe as previous. Kleiner (1996) describes the evolution of breaks on pipes in time using the model proposed by Shamir and Howard (1979), but he considers more rehabilitation alternatives and hydraulic constraints in optimization process. Kleiner (1996) and Werey (2000) use dynamic programming to propose optimal scheduling of renewal. LeGauffre et al. (1999) propose a multi-criteria analysis to determine classes of deteriorated pipes in a network depending on criteria linked with the pipe characteristics itself and it's environment, using an ELECTR-TRI method to propose a classification of pipes according to priority of replacing. It appears that the link between hydraulic operation and structural deterioration is not currently done. Therefore, models based on genetic algorithms didn't involve structural deterioration of pipes trough statistical models in decision-making process. The main insufficiency is relative to the non-consideration of the whole network, pavement state and hydraulic operation in renewal decisions. Concerning the methodology, the use of dynamic programming gives good results at the scale of a pipe and for small networks.

We propose a hybrid approach based on the use of statistical model, hydraulic simulation and Genetic Algorithm with a multi-objective optimization.

WATER NETWORKS RENEWAL AND GENETIC ALGORITHM

Genetic Algorithm is Evolutionary Algorithm based on natural selection and adaptation of species. The Principe of the algorithms is to code a character, proprieties or variables using sequence of codes. Developed by Holland (1975) and performed by Goldberg (1994). They were largely used in optimization of tasks scheduling, project planning, water networks design and maintenance. Genetic algorithms consider a set of design variables translated using codes. Helping with stochastic generations, genetic algorithm forms a set of initial possible solutions called population. From initial population, the algorithm explores the solutions space by creating new solutions set using genetic operators, by combining solutions from initial population. Genetic Algorithm was widely used for renewal of water networks, Halhal et al. (1997) propose an approach based on messy genetic algorithm applied to water network considering a function of hydraulic benefit and technical constraints by a multi-objective optimization assisted with hydraulic simulations. Dandy and Engelhardt (2001) propose an optimization model based on genetic algorithm, where the economic criteria consider the deterioration of pipe. Prediction of failures is obtained depending on pipe material, trough linear regression of breaks data. The model doesn't consider reliability index of pipes. Savic and Walters (1997) propose an application of genetic algorithm for specific constraints and considering particular objective function. It appears that several methods are adapted to a specific context or number of variables. Our approach involves Genetic Algorithm for optimization. Its takes into account alternatives of intervention on network and use environment variables (soil occupation and nature, material, length, diameter, installation date, previous breaks) to describe structural deterioration of pipe, trough statistical model. We include also the Hydraulic Critical Index to assess the hydraulic importance of each pipe, by simulating break on a given pipe and measure the impact of its unavailability on the other pipes. The analysis of hydraulic performance of network is also checked by hydraulic simulation for each proposed solution. The treated problem represents a multi-objective problem, characterized by technical objective given by pressure measure and economic objective given by cost measure. For these problems, different evolutionary algorithms had been proposed, specially for rehabilitation of water networks: Niched Pareto Algorithm NPGA proposed in Halhal et al (1997), Non Sorting Genetic Algorithm used in Devi and Nam-Sik (2004). They ensure the research of non-dominated solutions according to Pareto dominance and preservation of diversity in population without an elitism approach. Other algorithm take into account elitism selection, like Strength Pareto Evolutionary Algorithm (SPEA) used in Cheung et al (2003) and Non-Sorting Genetic Algorithm II proposed by Deb et al (2000).

PROBLEM FORMULATION

The use of Genetic algorithm requires an accurate definition of design variables, objective functions and of problem's constraints. The design variables for the studied problem are the possible alternatives for interventions on networks, they resume works to be done at a given year, in order to enhance reliability and hydraulic performance of network. They are taken into account trough string of codes called "chromosome".

DESIGN VARIABLES

Design variables are defined as integers between 1 to 4. We consider the code 1 for the alternative to do nothing, it translate the reparation of pipe if break occurs. The code 2 is assigned to the alternative to rehabilitate that consists in modifying hydraulic characteristics of pipe without replacing it. We enhance roughness and hydraulic capacity by relining or cleaning. The code 3 concerns the alternative to replace that consists to replace the pipe as previous (same diameter, but not necessary with the same material) and the last alternative has code 4, which consists to reinforce the pipe by enhancing diameter. The string length depends on the number of pipes considered in the model.

1	**3**	**1**	**3**	**2**	**...**	**4**	**1**	**2**

Pipe **1**   Pipe **p**

Figure1: The definition of policy and codes used trough a chromosome for ***p*** pipes

OBJECTIVE FUNCTIONS AND CONSTRAINTS

For the considered problem, Genetic algorithm don't use the objective function itself, but consider a fitness function which takes into account the evaluation of solutions according to several objectives. In order to answer to the problematic, we define two objective functions that describe the hydraulic performance of a given policy trough the pressure at nodes and an economic evaluation by assessing costs. The constraints considered ensure right hydraulic performance of network by minimum service pressure P_{min} and maximum pressure P_{max} to avoid an overpressure which can deteriorates pipes. The respect of financial resources available at a given time, by economic constraint is expressed into budget B(t). We take into account the state of roadway, in fact if pavement is recent, the only possible intervention is to repair pipe if a break occurs. Other alternatives are delayed for 5 years. At given time "t", for a set of design variables X_i , $i=\overline{1,4}$, ***p*** pipes in the network and two functions F_1 and F_2 :

$$\text{Minimum}F_1(X_1, X_2, ..., X_p, t) = \text{MinimumPressure}$$

$$\text{Minimum}F_2(X_1, X_2, ..., X_p, t) = \text{MinimumCost} \qquad (1)$$

$$\text{For } i=\overline{1,4}, \quad 1 \leqslant X_i \leqslant 4$$

Subject to:

$$P_{min} \leqslant F_1(X_1, X_2, ..., X_p, t) \leqslant P_{max} \qquad (2)$$

$$F_2(X_1, X_2, ..., X_p, t) \leqslant B(t) \text{ and } X_i \neq 1 \qquad (3)$$

For pipe j, if pavement is recent => V= 1 and Xj=1

HYDRAULIC CRITICITY INDEX

The consideration of previous breaks, age, costs of interventions and environment variables to select pipes to be renewal is not sufficient if we don't take into account the hydraulic role of each pipe in the network. Hydraulic Critical Index (HCI) translates the impact of unavailability of a given pipe on the whole network. For each pipe of the network, we simulate a break by closing temporarily the pipe and make hydraulic simulation. We compare the quantity of water delivered to consumers before (Q_{Before}) and after (Q_{After}) unavailability of pipe. Pipe is critical if water not delivered is important. For a pipe ***j***, HCI is given by:

$$HCI_j = \frac{Q_{Before} - Q_{After}}{Q_{Before}} \quad \text{With} \quad 0 < HCI_j \leqslant 1 \text{ and } j = \overline{1,p} \tag{4}$$

IMPLEMENTATION OF THE MODEL

Depending on data availability in the water utility, the optimization approach changes. In fact the selection of pipes candidates to renewal is based on failures prediction and the cost assessing of possible interventions on the pipes. We consider two possible situations.

AVAILABILITY OF BREAKS DATA SINCE THE INSTALLATION DATE

In the case of breaks data availability since the installation date of pipes, without environment data of pipe. We use the model proposed by Shamir and Howard (1979) applied also by Kleiner (1996) to predict failures and select pipes candidates to renewal. This model supposes that failure rate is constant and breaks occur according to a Poisson Process. We use an exponential function to describe break occurrence during time, considering date of starting simulation, we compare reparation costs with rehabilitation, replacement and reinforcement costs. The year of a renewal correspond to the date where repair costs become greater than other costs. For a given pipe, the total of breaks at a given year is described by the equation of Shamir and Howard (1979):

$$N(t)=N(t_s)e^{A(t+g)} \tag{5}$$

Where $N(t_s)$ is the number of breaks at the year t_s, A is break growth coefficient, and $t_s = t_0 + g$, where t_0 is the installation date and g is the age of pipe at the year t_s .

The cost of a policy is the sum of all interventions costs on pipes. For a pipe with index i, $\forall i \in \{1,p\}$ where ***p*** represents the number of pipes in network. K,M and N are binary variables, which translates the alternative to be adopted according to design variables. We suppose that no reparation is done during the 10 years next replacement or reinforcement. The cost is given by equation below:

$$\text{Cost}(i,t)= \int_{t_s}^{t} K.M.N.N(t_s).e^{A(t-t_s)}.e^{a(t-t_s)}.(C_m + \Delta Q.P_{water}) + (1-K).M.(1-N)[C_{reh} + \int_{t_s}^{t} N(t_s).e^{A.t}.(C_m + \Delta Q.P_{water})] +$$

$$(1-K).(1-M).N.[C_r + \int_{t_s+10}^{t} N(t_s).e^{A.(t-10)}.(C_m + \Delta Q.P_{eau})] + (1-K).(1-M).(1-N)[C_f + \int_{t_s+10}^{t} N(t_s).e^{A.(t-10)}.(C_m + \Delta Q.P_{eau})] + V.\text{Penalty} \quad (6)$$

Where C_r is the average annual cost of replacement pipe per length of pipe, C_{reh} is the average annual cost of rehabilitation pipe per length of pipe, C_{rev}: the cost of roadway revetment, C_m represents unit cost of break reparation, K,M, N and V represent binary variables, P_{water} is the water price of cube meter, ΔQ is the annual quantity of water losses for each pipe, r is actualization rate. The penalty included in equation (6) translates the effect of the legislation about excavation in certain road. If the roadway is reconditioned from less than 5 years, the only intervention possible is to repair pipe. Penalty allows discarding policies they propose other alternatives than to do nothing. Objective function F_2 is given by equation:

$$F_2(X_1, X_2, ..., X_p, t) = \sum_{j=1}^{p} \frac{1}{HCI(j,t)} . \text{Cost}(j,t) \quad (7)$$

AVAILABILITY OF BREAKS AND ENVIRONEMENT DATA DURING OBSERVATION WINDOWS

In this case, we dispose of less breaks data and ignore the breaks occurred before starting observation. We focus on pipes with important breaks during observation windows. A threshold related to breaks and age of each pipes is determined. For previous breaks we considers that the threshold is equal to 3 breaks as considered in Andreou (1986) and age between 40 and 45 years. To determine the pipes candidate to renewal, we asses the time between the last failure and the next one for pipe with 3 previous breaks, the pipe will be selected if the date to next breaks corresponds to the date of simulation. In the other case, we select the pipe with more than 3 breaks and age greater than 45 years. For the other pipes the only possible alternative is to repair if break occurs. Assessing time between third breaks and the next one is ensured by the survey function S(t) of PHM Model, which is given below.

$$S(t) = \exp[\ -\exp(\frac{-\sum \beta_i Z_i}{\sigma}).t^{\frac{1}{\sigma}}] \quad (8)$$

Where Z_i represent covariates related to environment variables, β_i regression coefficient and σ parameter obtained from data available. Considering the windows observation [t_a, t_b],

asses the time between the third (occurred at time t_3 and the next failure for a probability of occurrence P(t) more than 0.5, the date ***t*** of occurrence of the next break is obtained from :

$$P(t) = \frac{\exp[\ -\exp(\frac{-\sum \beta_i Z_i}{\sigma}).(t - t_3)^{\frac{1}{\sigma}}]}{\exp[\ -\exp(\frac{-\sum \beta_i Z_i}{\sigma}).(t_b - t_3)^{\frac{1}{\sigma}}]} = 0.5 \tag{9}$$

Considering pipes candidates to renewal, at a given time ***t***, for a pipe ***j***:

$$\mathrm{Cost}(j,t) = (K.M.N.C_m.\mathrm{Penalty} + (1-K).M.(1-N).C_{reh} + (1-K).(1-M).N.C_r + (1-K)(1-M)(1-N).C_f).e^{-rt} \tag{10}$$

Expression of the economical objective function F_2 is given by equation (7).

MULTI-OBJECTIVE OPTIMIZATION

The problem treated is a multi-objective problem, several resolution methods exists. The difficulty is how to discriminate solutions according to the two objectives and constraints considered in our study: hydraulic performance and available fund. To avoid risks to converge to a local optimum, we propose a multi-objective approach using Pareto ranking to determine non-dominated solutions. The approach proposed is based on the Non Sorting Genetic Algorithm (NSGA) implemented by Sirvinas and Deb (1994). Comparing with the algorithm used in Devi and Nam-Sik (2004) for design of water distribution networks, we consider integer codes for the design variables, the ranking procedure remain the same, but we consider phenotypic[4] distance to calculate sharing fitness, two points crossover and bite-wise mutation.

FITNESS DEFINITION

After selection of pipes to be renewed, the genetic algorithms generate a set of possible solutions trough initial population of size ***m***. According to the two objectives F_1 and F_2 we rank solutions in order to determine Pareto frontiers of non-dominated solution. Depending on rank, we evaluate fitness value of each solution. For non-dominated solutions of first rank we assign value (***1/m***) to fitness. In order to ensure diversity in population, we define shared fitness, which depends from distance between two solutions belonging to the same rank. Similar procedure with greater fitness is applied for other ranks. Shared distance is defined as:

$$d_{ij} = \sqrt{(F_{1i} - F_{1j})^2 + (F_{2i} - F_{2j})^2} \tag{13}$$

$sh_{ij} = 1 - (d^2{}_{ij} / \sigma_{share})$ If $d_{ij} \leqslant \sigma_{share}$ else $sh_{ij} = 0$ and $sh_{ii} = 1$, σ_{share} specified parameter

$$\text{Shared fitness (i)} = \frac{\text{fitness}}{\sum_j sh_{ij}} \tag{14}$$

[4] Phenotypic distance is given by Euclidian distance considered in objective functions space.

APPLICATION

After description of the optimization model, we present an application on network cited in Kleiner (1996). The example was adapted and only description data of pipe and cost data were used. The network studied is composed by 12 pipes and 1 tank for distribution water. The representation of network and pipe's data are given below. The description of failures data is obtained by exponential smooth according to equation(5). For each pipe we determine the evolution of breaks depending on the age of pipe. The table below resumes parameters of smooth of each pipe according to Table1 and breaks data available from installation date to 1995 (last observation).

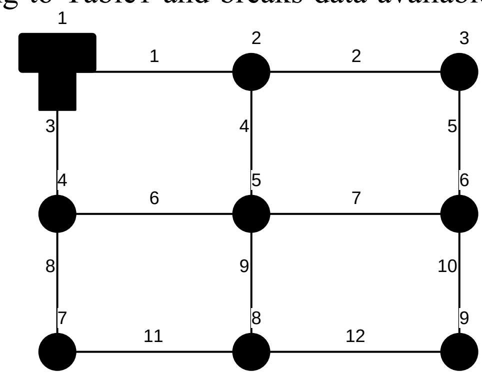

Figure 2: Network considered ins simulation

Table 1: Characteristics of water network at the beginning of simulation

Pipe	Length (m)	Diameter (mm)	Roughness (HW)	Installation date	A	N(to)	HCI	1/HCI
1	600	250	56	1945	0.07	0.05	1.00	1.00
2	800	150	42	1945	0.08	0.11	0.41	2.42
3	400	200	85	1945	0.05	0.11	1.00	1.00
4	500	200	62	1947	0.05	0.04	0.69	1.45
5	700	150	40	1950	0.08	0.09	0.19	5.33
6	600	200	41	1953	0.08	0.09	0.25	3.92
7	900	150	39	1953	0.08	0.09	0.41	2.42
8	500	200	55	1958	0.08	0.14	0.73	1.38
9	800	150	48	1960	0.07	0.18	0.24	4.23
10	700	150	43	1953	0.08	0.09	0.22	4.44
11	300	150	55	1963	0.08	0.11	0.25	4.02
12	600	150	56	1963	0.08	0.11	0.41	2.42

We assume that the simulation starts in 1996. Relating to HCI given in Table 1, the most important pipes are pipe 1 and 3, because of the unavailability of one of them the deliver of water to all nodes is stopped. Trough the HCI model will take into account the importance of each pipe in the hydraulic operation of water network, after assessing HCI for each pipe, we define initial parameters of Genetic Algorithm. We consider a set of ***50*** string forming the initial population, ***100*** generations, probability of crossover ***Pc=0.95*** and mutation probability ***Pm=0.015***, for each simulation, σ_{share} ***=18000***. We assume that available budget is equal to ***300.000 units*** and pressure must be comprised between ***20*** and ***45 m***. Results for year 1 are presented in Figure 2.

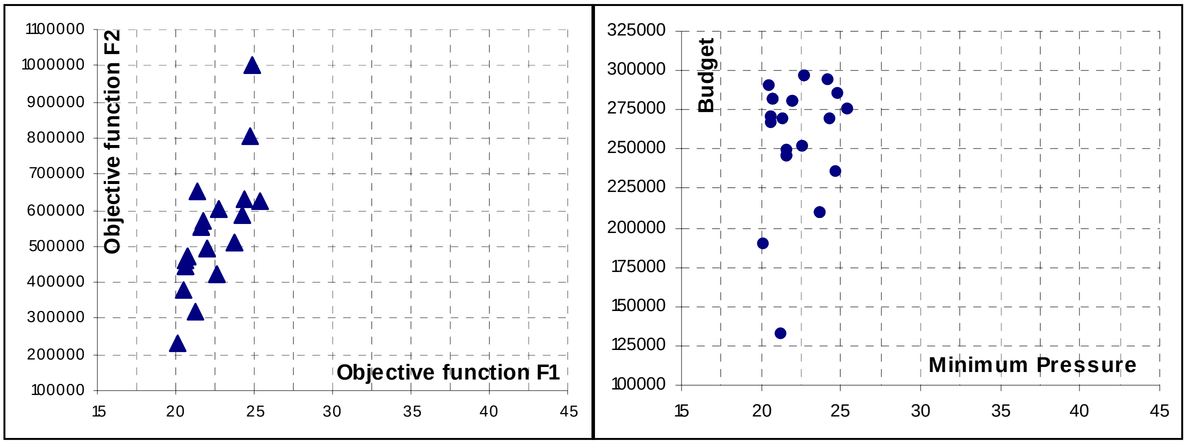

Figure 2: Some non-dominated solutions and avalaible budget at year 1

The plot at the right, show a set of non-dominated solution according to the two objectives. For problem treated, the budget avalaible should be used on the right way in order to ensure an adequate renewal policy that takes into account the important pipe in network according to HCI and ensure the desired pressure for all nodes in the network. According to the plot at the left, we can see that all solutions proposed respect contrainst of pressure and budget avalaible. The selection of an adequate soltuion depends of analysis of the two graphics given by Figure 2. For given simulation, we take into account modifications decided in the previous simulation, we modify network trough pipe's caractristics and assess new value for HCI at each simulation. We propose a sequence of interventions on network along simulation horizon of 5 years. The renewal policy is given in Table 2, no rehebilitation alternative was selected. Solutions proposed respect constraints and takes into account the importance of each pipe in the hydraulic operation of the network. For year 1, the sequence selected proposes to replace pipe 1 and pipe 8 and reinforce pipe 11 to ensure the respect of constraints and hydraulic performance.

Table 2: One of possible Schedule of renewal depending to given non-dominated solutions

Pipe	1	2	3	4	5	6	7	8	9	10	11	12	Pmin	Pmax	Cost(u)
Year1	2	1	1	1	1	1	1	2	1	1	3	1	20.80	42.85	281500
Year2	1	1	2	2	1	1	1	1	1	1	1	3	29.37	44.1	279000
Year3	1	2	1	1	2	1	1	1	1	1	1	1	36.85	44.6	225000
Year4	1	1	1	1	1	2	1	1	1	2	1	1	37.34	44.47	195000
Year5	1	1	1	1	1	1	2	1	2	1	1	1	38.74	44.48	255000

CONCLUSIONS

The model gives good results and considers a several criteria linked with pipe's characteristics, important of each pipe in the network, desired pressure and available fund. The main improvement ensured by the proposed approach is to take into account break data to describe structural deterioration, helping with statistical model in the renewal decision process. Moreover, it exists more than one possible renewal policy, the advantage of the developed model is to propose several sequences. Each sequence is characterized by hydraulic performance and cost. The final decision is supported by the water utility manager. The next step is to improve convergence of considered algorithm and apply the model on a real data set.

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