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# Scheduling of Water Distribution System Rehabilitation Using Structured Messy Genetic Algorithms

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**Abstract**

A methodology is presented for the optimal design and scheduling of investment for the rehabilitation of water distribution networks. Based on the evolutionary programming technique known as Structured Messy Genetic Algorithms, the methodology utilizes a multi-objective formulation which improves the evolutionary process and provides non-dominated optimal solutions over a range of costs and benefits. The model is applied to an example—a small artificial network of fifteen pipes. The effects on the optimal solutions of varying parameters such as interest rate and inflation rate are also investigated.

**Keywords**

Water distribution, genetic algorithms, scheduling, multi-objective, optimization, rehabilitation, networks.

**1 Introduction**

Drinking water distribution networks are essential and expensive components of the infrastructure of all urbanized areas. Most systems have been developed over a period of time, and much of the pipework is of considerable age. Pipes and fittings gradually deteriorate, with internal corrosion and depositions causing loss of carrying capacity and a consequent increase in pumping pressures and energy costs, pressure fluctuations and inadequate pressure at customers' taps.

The high cost involved in remedial works, together with budget restrictions applied by water utilities, make phasing the only financially practicable rehabilitation strategy in most cases. It is therefore sensible that the money available be optimally invested over a period of time taking into account both the physical response of the system with time and the influence of financial factors such as inflation and interest rate.

As previously reported (Walters and Savic, 1996), early work using genetic algorithms (GAs) and similar evolution programs in the water engineering field centered on pipe sizing and layout of water distribution networks (Walters and Cembrowicz, 1993; Dandy et al., 1996; Savic and Walters, 1997). The problem of replacing a set of pipes in a network at minimum cost using a GA is given in Walters and Savic (1997). All these studies approach the problem of design or rehabilitation as a “one-off” capital expenditure problem. However, the degradation of water distribution systems and the change in their structural and hydraulic performance are not one-time problems but rather continuous problems over time.

A Structured Messy Genetic Algorithm (SMGA), devised by Halhal et al., (1995) and applied to find the best way to invest a limited fund for water distribution system rehabilitation as a “one-off” problem (Halhal et al., 1997), is extended in this paper to deal with the scheduling of works over some time horizon for the rehabilitation and expansion of such a system. The physical characteristics, the hydraulic performance, the consumer demands, and the topology of the network may all change during the period scheduled. The method defines the best rehabilitation options to be undertaken for each pipe in each year of the planning period in order to maximize the total benefit yielded by these operations while keeping the present worth of investments required over the period less than or equal to the available budget. As the present method is based on a multiobjective optimization (MOO) procedure (i.e., optimizing the competing objectives of cost and benefit), a range of solutions will be produced with costs less than or equal to the available fund. This allows a preferred solution to be selected which gives good value for money. The method was implemented on a standard PC and run using an example to demonstrate its suitability to this type of scheduling problem.

## 2 Problem Formulation

In this study, it is assumed that a limited budget has to be invested over a period of time in the rehabilitation of a water distribution system. The budget is assumed to be available whenever needed. For example, investment of the entire sum in the first year of the planning period is possible, although unlikely. It is assumed that the unused portion of the rehabilitation project budget is allocated to another short-term project or invested until required.

System demands usually increase with time, while system performance decreases, emphasising problems such as leakage, drop in pressure, and deterioration of water quality. A late improvement to a rapidly degrading system may engender large expenditure on repairing emergency breaks, leakage detection, investigation of complaints accumulated during the years preceding the system rehabilitation, and cause customer discontent and deterioration in social welfare. Therefore, the model must consider all problem facets to reflect the true objectives and concerns of water utilities and their customers in determining optimal rehabilitation schedules.

The method presented here determines, in a dynamic way, optimal schedules for the rehabilitation and/or expansion of an existing water distribution system over a period of time, where the aforementioned factors are taken into consideration. It consists of defining a set of good solutions for both the rehabilitation actions for individual links and the timing of those actions over the planning period, such that the sum of the benefit yielded during the planning period is maximized. The sum of the present value of the corresponding costs

is also minimized, while keeping the total cost below the budget allocated to the operation.

The problem can be stated analytically as a multi-objective optimization (MOO) problem, as follows:

$$\text{Maximize } f(i) = \sum_{t=1}^{\text{Period}} w(t) \cdot \text{Benefit}(i, t) \quad (1)$$

$$\text{and Minimise } F(i) = \sum_{t=1}^{\text{Period}} PV(\text{Cost}(i, t)) \quad (2)$$

Subject to

$$\sum_{t=1}^{\text{Period}} PV(\text{Cost}(i, t)) \leq \text{Budget} \quad (3)$$

where  $PV$  is the present worth value;  $\text{Benefit}(i, t)$  is the benefit of the solution  $i$  yielded in year  $t$ ,  $\text{Cost}(i, t)$  is the cost of rehabilitation operations of solution  $i$  in year  $t$ ; Budget is the total fund; and Period is the planning period (in years).  $w(t)$  is a weighting factor which favors an early improvement to the system taking into consideration aspects other than economic ones, such as environmental and social aspects. It acts as a counterbalance to the interest rate in influencing the distribution of investment over the planning period. It is set as an inversely proportional function of time, which can be represented by an equation such as  $1/(1+t)$ ,  $k/(1+t)$  or  $1/(1+k)^t$ , with a positive coefficient  $k$  and the time  $t$  (in years) of the planning period. In this paper,  $w(t)$  is set equal to  $1/(1+k)^{t-1}$ , with  $k$  (the social welfare index) taken in the range 0 to 0.1. Formula 1 then becomes:

$$f(i) = \sum_{t=1}^{\text{Period}} \frac{1}{(1+k)^{t-1}} \text{Benefit}(i, t) \quad (4)$$

Formula 4 can be defined as the sum along the planning period of the present value of the benefit with respect to the index  $k$ . Actually, a later benefit is somewhat devaluated with respect to the social welfare, while an earlier benefit is more effective. The simplified Formula 4 is as follows:

$$f(i) = \sum_{t=1}^{\text{Period}} PV_k(\text{Benefit}(i, t)) \quad (5)$$

with  $PV_k$  representing the present value factor with respect to the index  $k$ .

## 2.1 The Objective Functions

The problem is presented in a multi-criterion format with two objective functions: the present value of the benefit and the present value of the cost. The benefit itself is derived from four separate criteria aggregated for convenience into a single benefit, but which could be treated as separate objectives in a more general model.

### 2.1.1 The Benefit

The benefit is the overall measure of system improvement resulting from the adoption of a particular solution. It is determined for each year of the planning period by assessing defined performance criteria for the proposed system and comparing these with the predicted performance of the unimproved system for that year, taking into consideration any

changes with time in the system topology, component characteristics, and nodal demands. It combines four components, the improvement in carrying capacity, the physical integrity of the pipes, system flexibility, and water quality.

The benefit resulting from the improvement of the hydraulic performance in a specified year of the planning period is determined as the difference between the deficiencies in the unimproved network in that year and in the solution,  $i$ , found in the same year. The deficiency in a specified year is calculated from the sum of nodal pressure excesses and shortfalls ( $(j,t)$ ) weighted by the demand flows  $Q(j,t)$  of the nodes for the same year.

$$\text{Deficiency}(i, t) = (\alpha K_{\min}(t) + \beta K_{\max}(t)) \tag{6}$$

in which

$$K_{\min}(t) = \sum_{j \in jpm} \Delta(j, t) \cdot Q(j, t) \tag{7}$$

$$\text{and } K_{\max}(t) = \sum_{j \in jpx} \Delta(j, t) \cdot Q(j, t) \tag{8}$$

where  $jpm$  is the set of nodes with pressure below the minimum,  $jpx$  is the set of nodes with pressure above the maximum, and  $\alpha$  and  $\beta$  are global weighting coefficients which can be adjusted to give more emphasis toward increasing low pressures or decreasing high pressures.

For each year of the planning period, every solution is compared to the initial system. Each increase in low pressure of a node (or decrease in high pressure) is considered an improvement in the hydraulic performance, and therefore yields a benefit. However, when the increased pressure remains below zero, the improvement has no tangible effect because the problem in supplying the node still remains. A weighting coefficient was therefore introduced into the evaluation of pressure shortfalls which favors improvements having a tangible impact on the system and on the customers. For a node  $j$  having a pressure  $h_j(t)$  below the minimum  $h_{\min}(t)$ , in a year  $t$ :

$$\text{if } h_j(t) > 0 \quad \Delta((j, t) = \lambda[h_{\min}(t) - h_j(t)] \tag{9}$$

$$\text{if } h_j(t) < 0 \quad \Delta(j, t) = \lambda h_{\min}(t) - h_j(t) \tag{10}$$

where  $\lambda$  is a weighting coefficient greater than 1.

An improvement in physical integrity of the network pipes occurs when existing pipes susceptible to breaks and leaks are replaced by new ones considered break-free. It yields a benefit calculated as a function of the present value of the breakage repair costs over the planned period from the year these pipes are replaced.

An improvement in the flexibility of the network is achieved when new pipes are laid parallel to existing ones, thereby increasing the number of paths taken by water in reaching consumers. This gives rise to a benefit determined as a function of the number of new parallel pipes.

The water quality of a system improves when the length of old, corroded pipes is reduced because these are prime sites for the development of micro-organisms and discolored water. The corresponding benefit is determined as a function of the length of renewed and/or lined old pipes having a Hazen-Williams (HW)  $C$  coefficient below a specified limit.

Table 1: Unit costs for rehabilitation options.

Diam (mm)	New pipe	Clean & line pipe	Replace existing pipe
80	100	85	110
100	175	100	190
150	220	150	240
200	320	220	350
300	550	300	600
400	780	410	850
500	980	500	1050
600	1350	630	1500

This coefficient indicates the carrying capacity (smoothness) of the pipe and low values of  $C$  are indicative of pipes with tuberculation or heavy scaling (Walski, 1984).

The annual benefit is set equal to the sum of these benefits with the total benefit of a solution being the present value of the annual benefits over the planning period.

### 2.1.2 The Cost

The total investment is calculated as the sum of the present values of the costs of the rehabilitation actions scheduled for each year of the planning period. The amount of money spent in a prescribed year corresponds to the cost of renewing, replacing, and/or cleaning existing pipes, or laying new pipe lengths in that year. Table 1 shows typical rehabilitation costs per meter (units of currency unspecified) for a range of available pipe sizes.

## 3 The Multi-Horizon Optimal Scheduling Methodology

To schedule the optimal rehabilitation of a water distribution system over a fixed period of time subject to a fixed maximum budget, the proposed methodology uses a Structured Messy Genetic Algorithm (SMGA) coupled with a Multi-Objective Optimization (MOO) procedure (Halhal et al., 1997).

### 3.1 Structured Messy Genetic Algorithm (SMGA)

SMGA is a derivative of Genetic Algorithms (GA) with flexible coding and variable string length. Its principle consists of building up, in a structured manner, the complexity of the individuals in successive populations of solutions, corresponding to the natural development of complex life forms from single cell organisms. SMGA starts the process by considering one-element strings corresponding to a single decision variable, e.g., rehabilitation action for one pipe only. This is followed by the evaluation of all these strings using either single or multiple objectives depending on the problem at hand. The best individuals are then kept in an initial population. From elements of this population of one-element strings, subsequent populations of longer string elements are formed using two main processes: *concatenation* and a *conventional GA*.

The *concatenation* process consists of forming a new population of longer strings by

adding randomly chosen elements from the initial population onto selected individuals in the current population. The new population formed undergoes a *conventional GA* process for a number of generations until meeting a termination criterion, where a new population of longer strings is generated by the concatenation process. This operation continues until no improvement can be achieved after two concatenating steps, or the population strings reach a predetermined length.

### 3.1.1 Multi-objective Optimization

Water distribution system optimization involves several, often competing objectives. The combination of these into a single objective formulation requires the use of weighting factors. The values of the weighting factors are usually chosen on a subjective basis and will often require many adjustments and runs of the optimizer to find an acceptable solution to the problem. The present method partially circumvents this problem by using a multi-objective procedure. Two main criteria are defined and evaluated separately, namely benefit and cost, and each solution is assessed with respect to them individually. The final result is not a single solution but a set of good solutions of differing costs, known as a Pareto optimal set. This is a set of “non-dominated” solutions in which no solution is inferior to any other under both criteria.

GAs, in general, and SMGAs, in particular, are well suited to MOO since the search is conducted using a population of individuals within which multiple near optimal solutions can develop in parallel. To ensure an adequate distribution of solutions throughout the evolution and in the final Pareto optimal set, SMGA uses the concept of Pareto-optimality ranking and fitness sharing to evaluate and scale the fitness of individuals in a population.

### 3.1.2 Pareto Optimality Ranking

This is a rank-based fitness assignment proposed by Goldberg (1989) to effect equal probability of selection to all non-dominated individuals in a population. The method consists of finding and then assigning rank 1 to all non-dominated individuals in the current population and removing them from further consideration. Rank 2 is assigned to the next set of non-dominated solutions in the remaining population and then they are removed from contention and so forth. All rank 1 solutions are then assigned the same high fitness value, with progressively lower values assigned to the lower ranks. Another Pareto optimality ranking methodology has been proposed by Fonseca and Fleming (1993), where the rank of each individual is defined by one plus the number of individuals in the current population that dominate it. However Pareto optimality ranking alone does not guarantee a uniform distribution of the Pareto set, and the population may still converge to a single solution of the non-dominated set, a phenomenon known as genetic drift. To prevent such a problem, another technique known as fitness sharing is used.

### 3.1.3 Fitness Sharing

Fitness sharing was introduced by Goldberg and Richardson (1987) to prevent genetic drift and promote an adequate distribution of the whole Pareto set within the population. For the present application, fitness sharing is implemented by first arranging the current population into sub-populations according to cost. This is done by dividing the total available budget into several bands and grouping all the individuals having costs within a band into the same class or sub-population. The shared fitness is then defined as the raw fitness of the individual divided by the number of individuals belonging to its class.

### 3.2 Implementation

In the methodology presented here, rehabilitation decisions and their timing during the planning period are defined simultaneously. Each solution in the SMGA process is represented by a string split into three sub-strings:

- the location sub-string, which gives the references (pipe numbers) of the active decision variables in the system, i.e., which pipes are scheduled for rehabilitation. An example of the sub-string may be [3, 8, 14] denoting pipes 3, 8 and 14 selected for rehabilitation.
- the decision sub-string, which gives the coded rehabilitation decisions for the corresponding active variables. There are several possible decisions for each pipe such as laying new pipes of various diameters in parallel, replacing the existing one, or cleaning and lining. An example of the sub-string may be [2, 1, 1] denoting that rehabilitation option 2 is proposed for pipe number 3 and rehabilitation option 1 is proposed for pipes 8 and 14.
- the timing sub-string, which gives the timing in the planning period for the execution of the corresponding rehabilitation decisions. It also defines the timing of the corresponding expenditure. For example, the sub-string [2, 2, 4] determines that pipes number 3 and 8 (see the location sub-string above) are scheduled for rehabilitation in year 2 while pipe number 14 is scheduled in year 4.

The cost and the benefit are determined for each trial solution for each of the planning years as described below. The present values of the benefit and the cost over the planning period constitute the two main criteria which are used to determine the fitness value using Pareto optimality ranking and fitness sharing.

After generating a solution by the GA process, the method proceeds by evaluating the cost of the different rehabilitation decisions planned in the first year of the planning period (if there are any). Then the network structure, its nodal demands and its components' characteristics are altered in accordance with these decisions prior to performing a steady state hydraulic analysis to determine the nodal heads, which are used in the evaluation of the benefit. The process continues in the same way for the subsequent years. For each year, the cost of the different operations planned for that year is determined. The network is modified accordingly and analyzed to determine the nodal pressures from which the benefit corresponding to the year is calculated. At the end of the planning period, the present values of the different benefits and the costs over the planning period are calculated.

This cost and benefit are evaluated for each solution of the population. Once all the population members have been evaluated, the fitness of each solution is determined using Pareto optimality ranking and fitness sharing. A new population replaces the old one and a GA process is carried out normally with selection, crossover, and mutation for a specified number of generations. By adding a single element to each member of the population (a concatenating process) a new population of longer strings is formed. The new population itself evolves for a number of generations, dependent on string length, and the process continues until either the string length reaches an initially specified value (dependent on the total budget), or no improvement is achieved after two concatenating steps. A flowchart representation of the method is given in Figure 1.

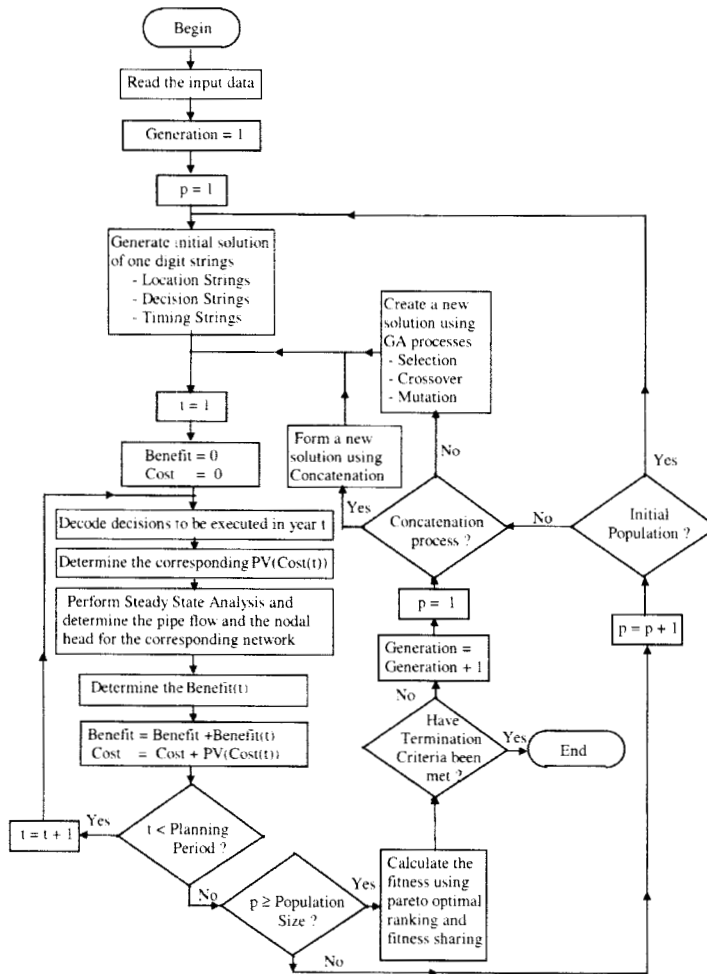


Figure 1: Flowchart representation of the methodology.



### 3.3 Advantages of the Methodology

#### 3.3.1 SMGA

The advantages that SMGA has over Standard Genetic Algorithms (SGA) lie in two main areas:

1. In rehabilitating a water distribution system, the optimization process alters only a relatively small number of arcs or other elements which are upgraded, renovated, or strengthened, even when the systems contain hundreds or thousands of such elements. SMGA encodes only the relatively small number of decision variables which are active. The active arc addresses, their rehabilitation decisions, and their timing are stored in the string, which increases in length through the evolution process. Comparisons of results for large network rehabilitation problems have shown superior performance for SMGA over conventional GA which use strings corresponding in length to the number of elements in the system (Halhal et al., 1997; Halhal, 1998). Therefore, SMGA explores the total search space necessary with strings of small maximum length, taking full advantage of the problem structure and easily handling large and complex water distribution systems in less computing time and memory space than is required for a conventional GA.
2. The size of space searched is reduced in comparison with a standard GA approach, which considers all combinations of elements as candidate solutions. This speeds up the process of finding the optimal or near optimal solutions, thus reducing the CPU time consumption. In fact, when only  $p$  elements (e.g., pipes) from  $q$  are considered, and each takes  $n$  alternative values, the search space contains a number of solutions equal to:

$$n^p \frac{q!}{p!(q-p)!} \quad (11)$$

while there are the much larger possible solutions in the search space when the total number of arcs,  $q$ , is considered as in conventional GAs.

#### 3.3.2 Multi-Objective Optimization

The use of MOO has several advantages over the conventional single objective approach:

1. Benefits from rehabilitation of a water distribution system do not increase linearly with cost but are subject to rapidly diminishing returns so that, beyond a certain cost, further increases in benefit become very expensive, and it is often more economical to choose a cheaper solution yielding lower benefits than a more expensive one which uses all the available budget. The range of solutions presented by the MOO approach enables a sensible and economic scheme to be chosen, particularly when there may be other projects competing for money from the same source.
2. The budget initially planned for a rehabilitation project is subject to change and may well be reduced before its release. The MOO approach yields a set of non-dominated optimal or near optimal solutions of differing costs containing solutions appropriate to a lower budget. The effects of budget changes on the benefits produced by the scheme will also be immediately apparent.

Table 2: Coding for each decision variable.

Code	Existing pipes	New pipes (mm)
1	Leave	80
2	Clean	100
3	Duplicate with diameter 150 mm	150
4	Duplicate with diameter 200 mm	200
5	Duplicate with diameter 300 mm	300
6	Duplicate with diameter 400 mm	400
7	Replace with same diameter	500
8	Replace with next largest size	600

### 3.3.3 SMGA in a MOO Procedure

In gradually building up the complexity of individuals, SMGA needs a large range of short string “building blocks” of differing cost which enable it to create useful long string solutions later in the process. MOO ensures the generation and maintenance throughout the evolution of populations of good partial solutions with diverse costs and benefits, rather than just low cost (low benefit) partial solutions available from a single objective (minimum cost) approach.

In its turn, the progressive way in which SMGA forms new solutions by growing strings of increasing length and increasing cost and benefit helps in the MOO approach. Solutions covering the full range of costs from zero to the available budget are developed gradually, starting with low cost solutions early in the process and developing the more expensive range of solutions as the evolution proceeds. In contrast, a conventional GA would struggle to generate an adequate range of low cost solutions for a MOO approach to this type of problem.

The link between SMGA and MOO is mutually beneficial and forms an efficient model capable of handling rehabilitation problems for large, complex, water distribution systems.

## 4 Example

Figure 2, shows a network of 9 nodes, 15 pipes, and 1 reservoir. Its rehabilitation is to be phased over a period of 10 years. The budget allocated to the work amounts to 3,000,000 units. A minimum pressure of 30m is sought at each node under design flow conditions. The nodal demand is given for the first year of the planning period and undergoes a constant annual increase of 3% during the ten year planning period, after which a steady growth rate of 1% is assumed. The annual growth of pipe break frequency is taken as 0.06. There are 8 possible rehabilitation decisions for each pipe as shown in Table 2. Depending on whether a pipe exists or a new pipe is considered, an appropriate code is taken from the table. The network data are given in Table 3, and unit costs of rehabilitation decisions are given in Table 1.

### 4.1 Results

The method yields a series of optimal or near optimal solutions of different costs up to the total budget. Ten classes of solutions characterized by their range of costs were adopted

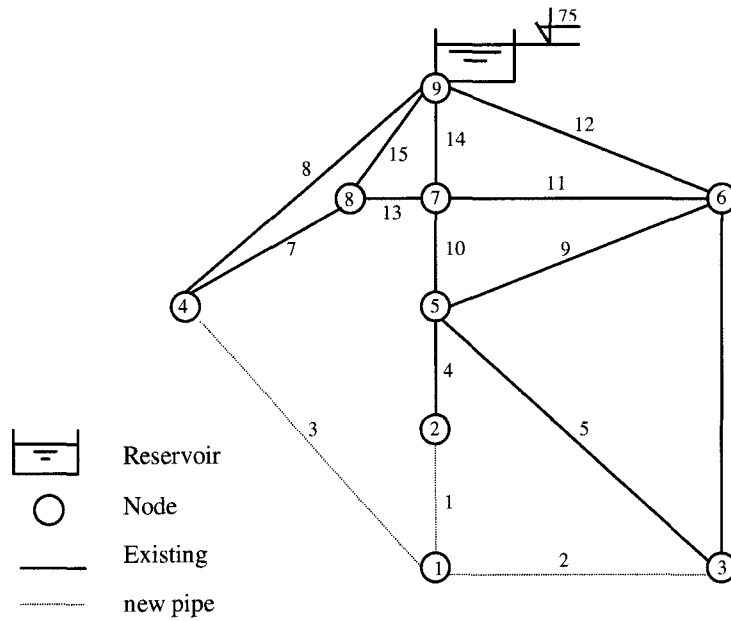


Figure 2: Network layout for the example in Section 4.

Table 3: Node and Pipe data.

ID	NODES		PIPES				
	Elev. (m)	Demand (l/s)	Diam. (mm)	Length (m)	Roughness (HW coef.)	Break Freq. (Brk/Km/yr)	Break Rep. Cost
1	20	15	New	1300	130	-	-
2	22	15	New	1500	130	-	-
3	20	30	New	1500	130	-	-
4	16	70	150	1700	70	0.5	6000
5	33	20	200	3100	100	1.1	8000
6	30	55	150	1200	120	-	-
7	21	25	300	1000	110	0.1	15000
8	22	15	150	2100	100	0.25	6000
9	75	Reservoir	150	1500	120	-	-
10			200	3600	80	1.7	8000
11			300	2000	100	0.1	15000
12			200	3000	110	1.02	8000
13			200	1000	120	-	-
14			150	1500	90	0.4	6000
15			200	1000	90	1.5	8000

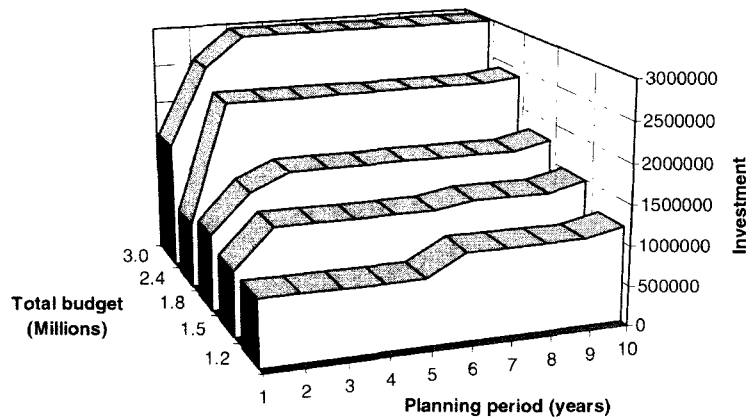


Figure 3: Investment schedules for various budgets (interest rate = 12%).

for this example, this number being easily increased or decreased. Figures 3 and 4 show the schedule of investment and the corresponding benefit over the planning period for five different budgets. They are given for a financial interest rate of 12%. The cumulative investment for any year corresponds to the sum of the present values of the different costs spent in the improvement of the network up to that year.

To promote useful improvements in hydraulic performance in the network, the coefficient  $\lambda$  of Formulae 9 and 10 is set equal to 100. That means that an increase in a deficient pressure resulting in a positive value produces a benefit 100 times greater than increases which still leave a negative improved pressure.

Figure 4 shows that after the first three years of increased benefits corresponding to large capital expenditure, the benefit decreases with time with a more gradual slope for the highest budget. This is due to the fact that most nodal pressures in the network start below target. Initial capital investment improves them, but as the network deteriorates and demands increase, pressure deficiencies increase. As the budget is limited to 3,000,000 units in this example, solutions belonging to the corresponding cost class are of most interest, keeping in mind that the same type of results are available for lower budgets.

#### 4.1.1 Interest Rates

To assess the influence of the interest rate on the investment schedule, three financial interest rates (FIR) were adopted: 0%, 8%, and 16% respectively. For each interest rate, the program was run 3 times and the best results corresponding to the budget class (3,000,000 units) were plotted on the graphs of Figures 5 and 6. The benefits over the planning period are shown for the three financial interest rates in Figure 6. The annual benefits are influenced by the financial interest rate variation, especially at the beginning and the end of the planning period with high initial benefit for lower interest rate and high final benefit for a higher interest rate.

Each improvement during a year is beneficial to the network for the succeeding years and affects their benefit. As the total benefit of a solution is set equal to the sum of the annual benefits during the planning period, high initial benefit solutions yield a high total

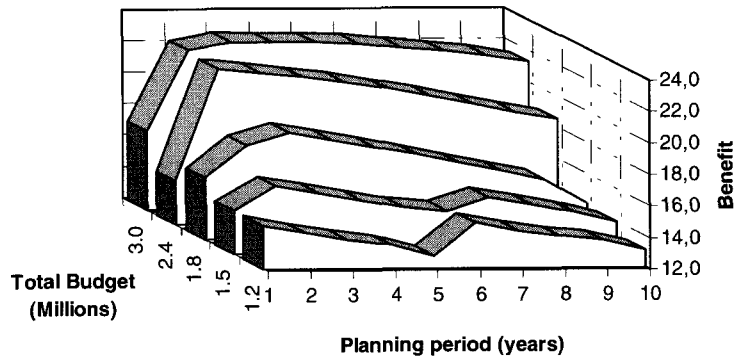


Figure 4: Benefit schedules for various budgets (interest rate = 12%).

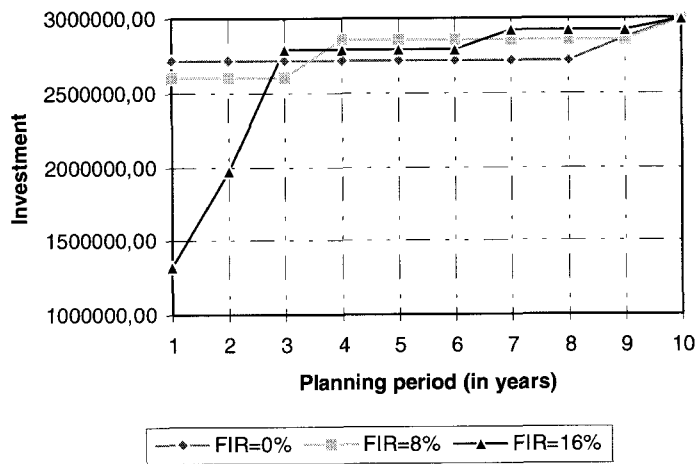


Figure 5: Investment schedule for various interest rates.

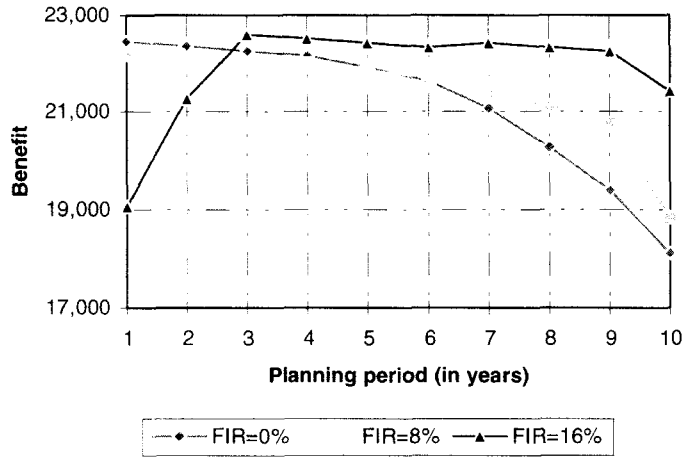


Figure 6: Benefit schedule for various interest rates.

benefit, and consequently are kept during the GA process as good solutions. Figure 5 shows that most of the investments are made during the first three years of the planning period, yielding high benefits early on. This limits the influence of the variation of financial interest rate on the investment process to the first quarter of the planning period.

#### 4.1.2 Benefit Evaluation Period

The influence of the interest rate in the scheduling of the investment would be more marked if the benefit was evaluated over a longer period. To test this influence, the period of evaluation of the benefit was extended to 20 years instead of 10 years of the planning period. The demand increase was taken equal at 1% after the planning period. Figure 7 shows the resulting investment over the planning period.

#### 4.1.3 Welfare Index

For the welfare of the community, it is important that the system performance is improved as soon as possible, and it is sensible to favor solutions which yield high benefits early in the process over those which, for the same global benefit, yield it later. Problems with the network will thus be tackled earlier in the planning period resulting in an improvement of the social well-being of those customers poorly supplied with water. To incorporate the greater importance placed on early improvements, the Welfare Index (WI) was introduced to enable a Present Value of future benefits to be derived. To assess the impact of the WI on the investment and benefit distribution over the planning period, three WI (0, 0.05, and 0.08) were introduced in the benefit formula for a financial interest rate of 12%. The results are plotted on the graphs of Figures 8 and 9. It can be seen that higher WI drives the process towards developing solutions with high initial investment and benefit.

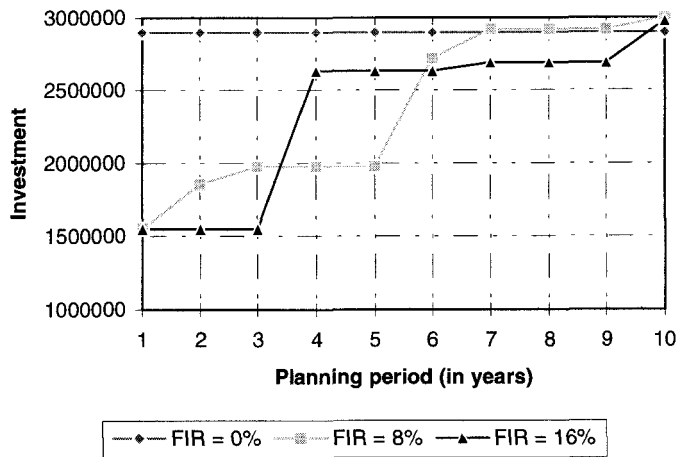


Figure 7: Investment schedule over 10-year period with evaluation of benefits over 20 years.

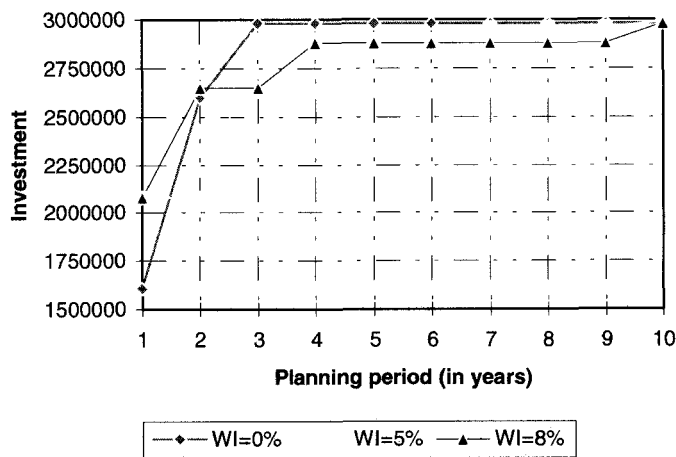


Figure 8: Investment schedule for various welfare indices (interest rate = 12%).

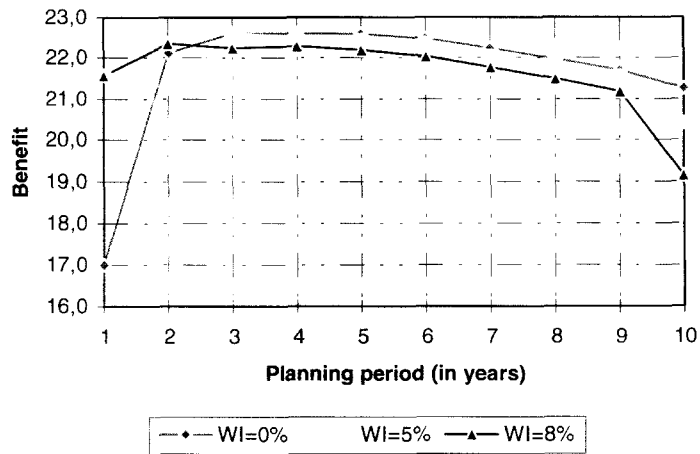


Figure 9: Benefit schedule for various welfare indices (interest rate = 12%).

#### 4.1.4 Inflation Rates

During the planning period, the costs of pipes, manpower, and energy normally increase, thereby influencing the investment decisions. To take into consideration these variations, three rates of increase for pipe costs, 0, 3%, and 7%, have been used in the process, and the corresponding best results for a financial interest rate equal to 12% are shown on in Figures 10 and 11. The figures show that high pipe increase rates (PIR) favor solutions with high initial investment and benefit.

#### 4.1.5 Pipe Roughness

The ability of pipes to carry flows diminishes with time because of tuberculation, corrosion, and deposition of excess calcium and sediment, modelled by an annual decrease in their Hazen-Williams (HW) coefficients. The investment and benefit over the planning period for three HW decrease rates (HWD), 0%, 2%, and 4%, are given in Figures 12 and 13 for an annual interest rate equal to 12%.

## 5 Conclusions

A multi-objective optimization method using SMGA was developed to find the optimal planning of the rehabilitation, upgrading, and/or expansion of a water distribution system subject to a limited funding. The method defines the different alternatives to be undertaken in the network pipes and their scheduling in the planning period, which yields the maximum benefit with respect to the invested money, taking into account the different internal and external time varying factors to the system under consideration.

The method yields a series of non-dominated solutions of differing costs up to the total budget allocated to the rehabilitation operation, permitting a judicious and flexible choice of the most convenient solution with respect to the available budget.



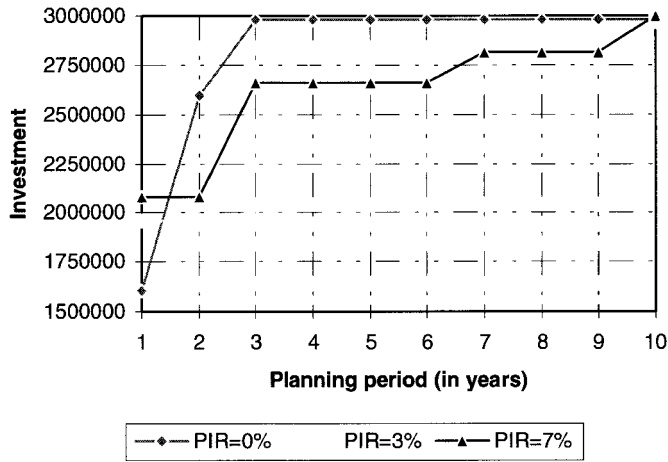


Figure 10: Investment schedule over 10-year period with evaluation of benefits over 20 years.

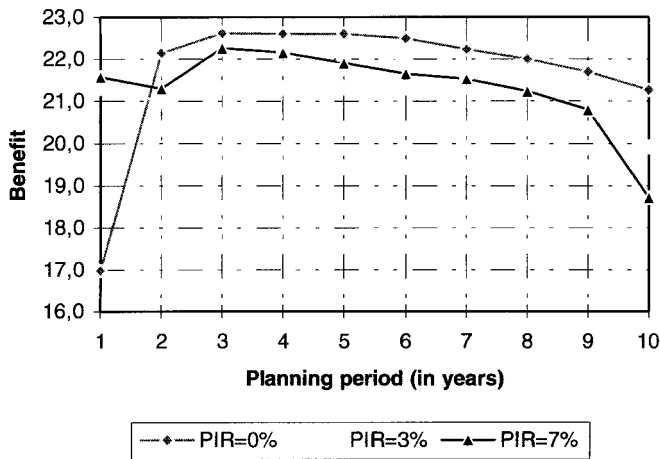


Figure 11: Benefit schedule for various pipe cost increase rates (interest rate = 12%).

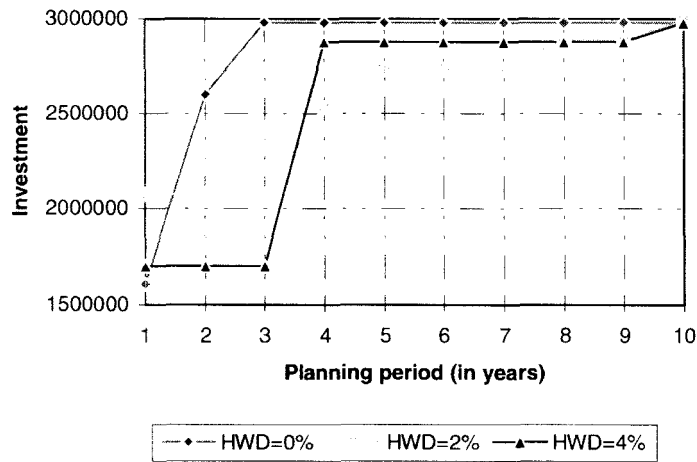


Figure 12: Investment schedule for various HW annual decrease rates (Interest rate = 12%).

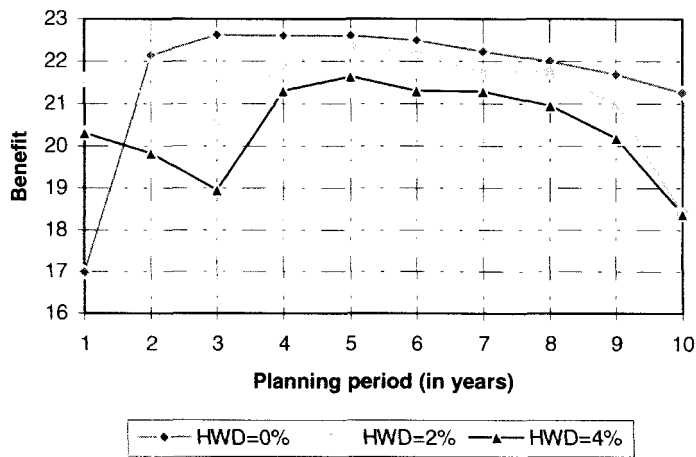


Figure 13: Benefit schedule for various HW annual decrease rates (Interest rate = 12%).

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## References

- Dandy, G. C., Simpson, A. R. and Murphy, L. J. (1996). An Improved Genetic Algorithm for Pipe network Optimization. *Water Resources Research*, 32(2):449–458.
- Fonseca, C. M. and Fleming, P. J. (1993). Genetic Algorithms for Multiobjective Optimization: Formulation, Discussion and Generalization. In Forrest, S., editor, *Proceedings of the Fifth International Conference on Genetic Algorithms*, pages 416–423, Morgan Kaufmann, San Mateo, California.
- Goldberg, D. E. (1989). *Genetic Algorithms in Search, Optimization, and Machine Learning*, Addison-Wesley, Reading, Massachusetts.
- Goldberg, D. E. and Richardson, J. J. (1987). Genetic Algorithms with Sharing for Multi-modal Function Optimization. In Grefenstette, J. J., editor, *Proceedings of the Second International Conference on Genetic Algorithms*, pages 41–49, Lawrence Erlbaum, Hillsdale, New Jersey.
- Halhal, D., Walters, G. A. and Ouazar, D. (1995). Structured Messy Genetic Algorithm Approach for the Optimal Improvement of Water Distribution Systems. *Proceedings of the GALESIA 95*, IEE Conference Publication No. 414, pages 406–411, IEE, London, England.
- Halhal, D., Walters, G. A., Ouazar, D. and Savic, D. A. (1997). Water Network Rehabilitation with Structured Messy Genetic Algorithm. *Journal of Water Resources Planning and Management*, 123(3):137–146.
- Halhal, D. (1998). Optimal Improvement of Water Distribution Systems. Doctoral Thesis, University of Exeter, Exeter, England.
- Savic, D. A. and Walters, G. A. (1997). Genetic Algorithms for the Least-cost Design of Water Distribution Networks. *ASCE Journal of Water Resources Planning and Management*, 123(2):67–77.
- Walski, T. M. (1984). *Analysis of Water Distribution Systems*, Van Nostrand Reinhold, New York, New York.
- Walters, G. A. and Cembrowicz, R. G. (1993). Optimal Design of Water Distribution Networks. In Cabrera, E. and Martinez, F., editors, *Water Supply Systems, State of the art and future trends*, Computational Mechanics Publications, pages 91–117, Southampton, England.
- Walters, G. A. and Savic, D. A. (1996). Recent Applications of Genetic Algorithms to Water System Design. In Blain, W. R., editor, *Hydraulic Engineering Software VI*, pages 143–152, Computational Mechanics Publications, Southampton, England.
- Walters, G. A. and Savic, D. A. (1997). Planning the Rehabilitation and Strengthening of Distribution Networks Using Genetic Algorithm Software. In Chilton, R., editor, *Proceedings of the Third International Conference on Water Pipeline Systems - Leakage Management, Network Optimization and Pipeline Rehabilitation Technology*, BHR Group Conference Series, Publication No. 23, pages 407–416, Mechanical Engineering Publications, London, England.