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Scheduling renewal of water pipes while considering adjacency of infrastructure works and economies of scale

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Abstract

Much research effort has been dedicated to the development of optimal strategies for rehabilitation and/or replacement of water mains. Some of the methods are intended for high-level planning of groups or cohorts of pipes, while others address low-level scheduling of individual water mains. This paper focuses on the latter aspect. An approach is proposed for the efficient scheduling of individual water mains for replacement in a short to medium pre-defined planning period and subject to various budgetary constraints. This approach also accounts for economies of scale considerations as well as harmonisation with other known infrastructure works. A multi-objective genetic algorithm scheme is used as a tool to search a vast combinatorial solution space, comprising various combinations of pipe replacement schedules.

Key words: Water mains, pipes, renewal planning, multi-objective genetic algorithm, roadwork, economies of scale.

Introduction

The optimal scheduling for replacement of individual water mains is a challenge that has been quite extensively addressed in the last two decades. Often this optimal scheduling scheme is coupled with a forecasting model of future breakage rates. Much research effort has been dedicated to the development of optimal strategies to rehabilitation/replacement of water mains, a good portion of which is suitable to high-level planning of groups, or cohorts of pipes. In the following brief literature review, we focus only on those methods intended to address individual water mains.

Shamir and Howard (1979) pioneered this field with their exponential deterioration model, that was suitable to cohorts of pipes. Walski and Pelliccia (1982) refined the exponential model by using previously observed breaks and diameter classes as additional contributing factors. Walski (1987) extended the exponential growth model to include the cost of water losses through leaking pipes and the cost of broken valve replacement. Woodburn *et al.* (1987) combined a nonlinear programming procedure with a hydraulic simulation program in a model designed to determine which pipes should be replaced, rehabilitated or left alone in order to minimize cost. Su and Mays (1988) introduced some probabilistic considerations to the Woodburn *et al.* model. Male *et al.* (1990) addressed the structural deterioration of water mains over time but did not consider the hydraulic capacity of the distribution system. Kim and Mays (1994) proposed a branch and bound scheme to improve on the Su and Mays (1988) model. Arulraj and Suresh (1995) introduced the concept of significance index (SI), which is an optimality criterion that can be applied heuristically to prioritize pipe rehabilitation.

Halhal *et al.* (1997) proposed an approach whereby four types of benefits (hydraulic, physical integrity, operational flexibility and water quality) were quantified and selection of pipe replacement/relining was performed on a double objective trade-off between maximizing benefits and minimizing cost (multi objective messy genetic algorithm was used as a tool). However, this model did not include the scheduling of pipe replacement. Herz (1999a, 1999b) proposed the KANEW model, which fits the Herz probability distribution to cohorts of pipes to forecast their residual life and generate long term rehabilitation plans. Kleiner *et al.* (1998a, 1998b) proposed an approach in which pipe breakage rate was modelled deterministically as an exponential function of age, and the subsequent scheduling scheme considered both network economics and hydraulic capacity over a pre-defined analysis period. Englehardt *et al.* (2000) provided a comprehensive review of issues to be addressed by pipe renewal strategies, as well as an account of much of the research effort that had been done to date (including for both cohorts and individual water mains). Dandy and Englehardt (2001) proposed a method using GAs to optimize pipe replacement scheduling and diameter selection.

Skipworth et al., (2002) developed *WILCO*, which is an integrated decision model that combines pipe whole Life Costing and hydraulic and physical analysis of the network to generate rehabilitation strategies that are then evaluated using genetic algorithms. Le Gauffre et al, (2004) proposed the *CARE-ARP* model (Computer aided rehabilitation of water networks - Annual Rehabilitation Program) that considers several performance indicators in a multi-criteria analysis (following the Electre-tri method, proposed by Mousseau and Slowinski, 1998) to identify critical pipes and establish priority for rehabilitation. Burn et al. (2003) developed PARMS (Pipeline Asset and Risk Management System) to prioritise groups of pipes for rehabilitation. Moglia et al. (2006) enhanced PARMS by incorporating risk analysis that examines the impacts of failure on the pipe physical environment. Dandy and Englehardt (2006) proposed an approach to schedule pipe replacement (5-year time steps) on a double objective trade-off between maximizing network reliability and minimizing cost. Here too, multi-objective GA was used as a tool. Eisenbeis (1994) proposed to use the expected number of breaks and their associated costs (to be minimised) for the selection and scheduling of deteriorated pipes for renewal. Renaud et al. (2007) introduced *SIROCO*, a decision support tool that performs multi-criteria analysis (criteria include hydraulics, and forecasted failures) to select pipes for renewal in the short term, while considering possible coordination with other public works (sewers, roads, etc.)

In this paper we propose a method for the optimal scheduling of individual pipes for replacement, while considering practical issues such as harmonizing pipe replacement with known roadwork and economies of scale. Although this method is not restricted to any planning horizon length, it is deemed most suitable for short to mid-term planning (say, 5 years) due to practical considerations such as municipal budgetary planning horizon, confidence (or rather lack thereof) in longer term forecasting of breakage rates in individual water mains and likelihood of unforeseeable changing conditions. The proposed method is not limited to any specific breakage rate prediction model, rather it requires the forecasting of expected number of breaks for any individual pipe in a pre defined time period. The length of this time period is discussed in the following sections.

The proposed method is currently limited to the consideration of pipes breakage frequency and the economics of their replacement. Future work will strive to encompass other factors, such as hydraulic performance, network reliability and even water quality issues, however due to the dimensionality of the solution space these endeavours will present substantial challenges.

The rest of this paper is organized as follows. The second section provides definitions and assumptions underlying the proposed approach, the third section describes the solution method, the fourth section provides an illustrative example, the fifth section provides a brief discussion on the merits and deficiencies of the approach and finally summary and conclusions are provided in last section.

Problem statement, definitions and assumptions

The problem addressed in this paper is generally expressed as follows: "Given a water distribution network with an inventory of N individual pipes, and given a planning horizon of T years, where $k_{i,t}$ ($i = 1, 2,\ldots, N$) is the forecasted expected number of breaks for pipe i in year t, and given a pipe renewal budget B_T, how should the pipes be scheduled for renewal while maximizing economic utility?". Our definition of "economic utility" will be elaborated on later in this section. The term "individual pipe" can mean different things to different people. For practical reasons we did not attempt to provide a universal definition, rather we accept the implied definition of the owner of the network, as it is manifested in the inventory database.

Pipe failure costs

As mentioned earlier, $k_{i,t}$ is the forecasted expected number of breaks in pipe i at year t. We observe five different costs that are potentially associated with pipe failure. We denote the cost of failure repair by C_i^{rep}, cost of expected direct damage (e.g., to adjacent infrastructure, basement flooding, road damage) by C_i^{dir}, cost of indirect damage (e.g., accelerated deterioration of roads, sewers, etc.) by C_i^{indir}, cost of water loss by C_i^{wat}, and social cost (e.g., disruption, time loss, pollution, loss of business, etc.) by C_i^{soc}. The total cost of failure Cf_i in pipe i is therefore

$$Cf_i = C_i^{rep} + C_i^{dir} + C_i^{indir} + C_i^{wat} + C_i^{soc} \tag{1}$$

Total cost associated with pipe replacement timing

The total cost associated with pipe replacement timing is impacted on one hand by failure costs (or failure avoidance gains) and on the other hand by the time value of capital outlay. The present value (PV) of the total cost associated with pipe i, which is replaced at year t is given by

$$C_{i,t}^{tot} = CR_{i,t}e^{-rt} + \sum_{j=1}^{t} k_{i,j}[(C_i^{rep} + C_i^{dir} + C_i^{wat})e^{-rj} + C_i^{indir} + C_i^{soc}] \quad (2)$$

where $CR_{i,t}$ is the cost of replacing pipe *i* at year *t*, e^{-rt} is the exponential form of discounting and *r* is the discount rate. Note that the indirect cost and social cost components of pipe failure are not discounted here (there is no consensus on the merit of discounting social costs). Note further that for public projects such as water main works it is appropriate to use "social discount rate", which is significantly lower (typically 1% - 3%) than financial discount rate (see e.g., Hufschmidt et al., 1983). Equation (2) also implies that the number of failures expected to occur on the new replacement pipe during the planning period *T* is assumed to be negligible. The assumption is justified for relatively short planning periods, except perhaps in rare cases where pipes are subject to extremely fast deterioration Dandy and Engelhardt (2006), for example did consider cost of repair for new pipes in a short planning period).

The literature reflects (e.g., Shamir and Howard, 1979; Kleiner *et al.* 1998a) that equation (2) generally describes a convex present value cost function as illustrated in Figure 1. Herz (1999b) agreed that the cost function is generally convex but observed that often it is very flat, especially in the inclining branch (the right side) of the curve, creating a "hammock" shaped function. The time (t_i*) when the total cost of pipe *i* is minimum is the point at which the marginal (discounted) cumulative cost of failure rate, which is essentially the expected (discounted) cost of failure at year t_i*, equals the marginal savings due to deference of replacement (i.e., the product of cost of pipe replacement and discount rate).

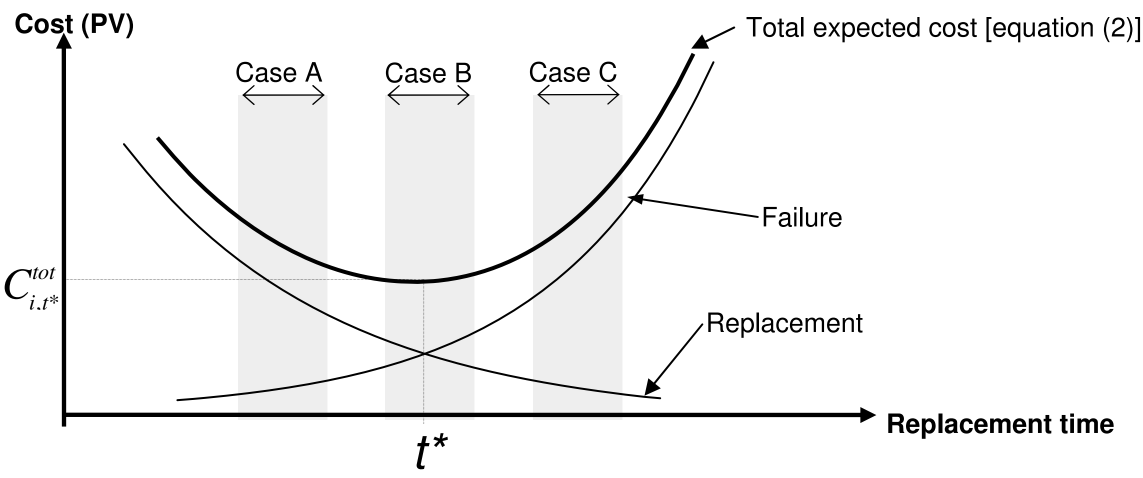

Figure 1. Costs associated with replacement timing

If the expected discounted cost of failure of pipe i at year t is denoted by $\Delta Cf_{i,t}$ and the marginal savings in deferring replacement of pipe i from year t to $t+1$ is denoted by $\Delta CR_{i,t}$ then the relationship between $\Delta Cf_{i,t}$ and $\Delta CR_{i,t}$ indicates where year t is in relationship to year t^*. When $\Delta Cf_{i,t} << \Delta CR_{i,t}$ (Case A in Figure 1) then t is far to the left of t_i^*; when $\Delta Cf_{i,t} \approx \Delta CR_{i,t}$ (Case B in Figure 1) then t is in the vicinity of t_i^*; and when $\Delta Cf_{i,t} >> \Delta CR_{i,t}$ (Case C in Figure 1) then t is far to the right of t_i^*. Correspondingly, when planning window T for a given pipe is to the far left of a t_i^*, then the value of $C_{i,t}^{tot}$ from equation 2 will tend to be minimum at the last year of T or beyond. When planning window T for a given pipe is to the far right of t_i^*, then the value of $C_{i,t}^{tot}$ will tend to be minimum at the first year of T. When planning window T for a given pipe is around t_i^*, then the value of $C_{i,t}^{tot}$ can be minimum at any year of T.

Based on Equation (2), for each pipe i we can find the year $\hat{t}_i$ for which $C_{i,\hat{t}}^{tot}$ is the smallest in the period of $2T+1$ years. The assumptions about the shape and properties of equation (2), help to distinguish between the following three cases:

1. If $\hat{t}_i > T$ then $\hat{t}_i$ is located to the left of t_i^* for pipe i (i.e., case A in Figure 1)
2. If $2 \leq \hat{t}_i \leq T$ then $\hat{t}_i$ coincides with t_i^* for pipe i (i.e., case B in Figure 1).
3. If $\hat{t}_i = 1$ then during T, $\hat{t}_i$ is located to right of t_i^* for pipe i (i.e., case C in Figure 1).

Note that if t_i^* happens to coincide with the first year of the planning period it would also qualify as case B.

It is clear that in cases 2 and 3, barring any additional cost considerations, if pipe i is to be replaced then replacement should be carried out at year $\hat{t}_i$, where the total cost C_{i,t^*}^{tot} (equation 2) is minimum. In case 1, it is clear that pipe i should not be replaced at all during planning period T because C_{i,t^*}^{tot} is obtained when replacement is carried out beyond planning period T. However, as will be explained in the next subsection, some situations could exist where economies of scale considerations would make it cost effective to replace a pipe during planning period T even if $\hat{t}_i$ falls later.

A penalty matrix $\boldsymbol{Q}$ (N x ($2T$)) is defined, whose elements are $q_{i,t} = C_{i,t}^{tot} - C_{i,\hat{t}}^{tot}$. Matrix $\boldsymbol{Q}$ is named "penalty matrix" because each element defines the penalty associated with deferring (or promoting) the replacement of pipe i from year $\hat{t}_i$ to any other year t (in subsequent text we refer to this notion as "time-shifting penalties"). The reason why $\boldsymbol{Q}$ has $2T$ columns (as opposed to $2T+1$ years of forecasted breaks) is explained below.

Why consider 2T years in penalty matrix, Q?

As described earlier, the so-called Case A (Figure 1), where $\hat{t}_i > T$, is problematic because it is not known *a priori* how far into the future the true minimum t_i* lies and whether it is more economical to wait until then even if an opportunity arises to save cost (due to economies of scale) by replacing during the current planning period T. Thus, there is a practical need to reduce the problem dimensionality because contiguity calculations are computationally demanding. To this end, the following assumption was made:

If for pipe i, $\hat{t}_i > T$ (i.e., case A in Figure 1) and $\hat{t}_i \leq 2T$ then there is some likelihood that economies of scale savings might outweigh time-shifting penalties. However, when T is not too short (e.g., $T > 3$ years) the likelihood of this happening is very little if $\hat{t}_i > 2T$ and therefore it is reasonable to assume that the replacement of pipe i is better deferred to the next planning period.

Consequently, all pipes i with $\hat{t}_i = 2T+1$ are removed as candidates for replacement in planning period T (also referred to as 'planning window). Further, penalty matrix $\boldsymbol{Q}$ is computed in consideration of only pipes i for which $\hat{t}_i \leq 2T$. Note that the actual scheduling of pipe replacement is done only for the T years of the planning period.

Economies of scale in pipe replacement cost

Pipe replacement cost was assumed to have two components, fixed and variable. The fixed component, M, is termed 'mobilization component' and is taken as a lump sum. Although in reality M may vary with the type and size of each pipe, for simplicity it was assumed to be approximately equal for all small (up to 12" diameter) distribution mains. Mobilization component comprises costs such as setting up the job site, signage, discovery and marking of adjacent infrastructure, etc. The variable component, Cr_i, is the length-unit cost ($/m) of replacing pipe i and it depends on pipe material, diameter, location and possibly other special circumstances (e.g., difficult access, rocky terrain, etc.). The cost of replacing pipe i, of length l_i is therefore

$$CR_i = M + Cr_i l_i \tag{3}$$

To account for economies of scale, the following assumptions are made about the mobilization and variable components of pipe replacement cost:

- A quantity discount, $D_{t,m}$, is applied to the replacement of pipes $V_{t,m}$ of the same material m, when their replacement is carried out in the same year t (pipes in subset $V_{t,m}$ are assumed to belong to the same replacement project). This discount is proportional to the total length of pipes in $V_{t,m}$

$$D_{t,m} = \begin{cases} 0 & ; \quad L_{t,m} < L_{\min} \\ \dfrac{d_m^{\max}(L_{t,m} - L_m^{\min})}{L_m^{\max} - L_m^{\min}} & ; \quad L_{\min} \le L_{t,m} \le L_{\max} \\ d_m^{\max} & ; \quad L_{t,m} > L_{\max} \end{cases} \tag{4}$$
$$L_{t,m} = \sum_{\forall i \in V_{t,m}} l_i$$

where $d_m^{\max}$ is the maximum quantity discount available foFr pipe material m, and $L_m^{\max}$ and $L_m^{\min}$ are pipe length quantities defined by the contractor. This quantity discount function is clearly illustrated in Figure 2.

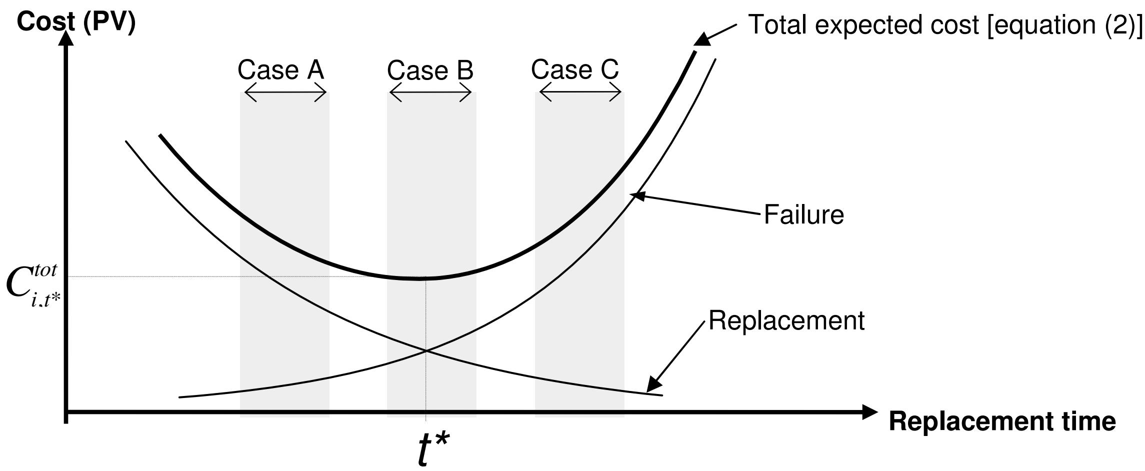

Figure 2. Variation of quantity discount with pipe length

- Cost reduction is also possible when pipe replacement is coordinated with scheduled roadwork. It is assumed that the unit cost (variable component) of pipe replacement is discounted by p_i (e.g., \$/m or % of cost) if pipe i is replaced at the same year t that the pavement overlying it is scheduled for renewal. The total (nominal) cost of replacing pipe i at year t then becomes:

$$CR_{i,t} = M + (Cr_i - \alpha_{i,t} D_{m,t} - \beta_{i,t} p_i) l_i \tag{5}$$

where $\alpha_{i,t}$ and $\beta_{i,t}$ are binary variables so that $\alpha_{i,t} = 1$ if pipe i is of material m otherwise $\alpha_{i,t} = 0$; $\beta_{i,t} = 1$ if the road overlying pipe i is renewed in year t, otherwise $\beta_{I,t,} = 0$.

- It is reasonable to assume that only one mobilization component is levied if pipe j is contiguous to pipe i (both share the same node) and both are replaced in a given year t as they form part of the same replacement project,

$$\begin{aligned} CR_{i,t} + CR_{j,t} = M + (Cr_i - \alpha_{i,t} D_{m,t} - \beta_{i,t} p_i) l_i + \\ (Cr_j - \alpha_{j,t} D_{m,t} - \beta_{j,t} p_j) l_j \end{aligned} \tag{6}$$

This concept can be extended to u contiguous pipes that are replaced in a given year t, defined as contiguity U:

$$CR(U) = M + \sum_{\forall i \in U} (Cr_i - \alpha_{i,t} D_{m,t} - \beta_{i,t} p_i) l_i \tag{7}$$

The revised cost of replacing pipe i at year t, where pipe i belongs to contiguity U (assuming for convenience that all mobilisation costs are divided amongst all pipes in contiguity U relative to respective lengths) becomes

$$CR_{i,t} = \left[\frac{M}{\sum_{\forall i \in U} l_i} + \sum_{\forall i \in U} (Cr_i - \alpha_{i,t} D_{m,t} - \beta_{i,t} p_i) \right] l_i \tag{8}$$

Economies of scale considerations may typically create situations where $C_{i,t}^{tot} < C_{i,\hat{t}}^{tot}$. For example, if roadworks are planned for pipe *i* in year t_i and $t_i \neq \hat{t}_i$ it may be beneficial to shift pipe replacement to year *t* if the savings due to roadwork are greater than the penalty for shifting from year $\hat{t}_i$ to year *t*. A similar situation can arise when pipe *i* contributes to complete a contiguity in year *t*, thus creating cost savings that possibly exceed penalties due to shifting (deferral or advancement). These situations create economies of scale savings that require the introduction of negative penalties (benefits) in penalty matrix $\boldsymbol{Q}$. It should be noted that quantity discount and mobilisation savings due to pipe contiguity cannot be computed *a priori* for each pipe, rather they are computed upon the evaluation of an entire candidate solution.

Budget assumptions

The total pipe replacement budget for the entire planning horizon (*T* years) is denoted by B_T. We consider two budget scenarios, namely annual budget and global (non-restricted) budget. In the annual budget scenario, B_T is divided into annual portions B_t and the total cost of pipe replacement in year *t* must not exceed B_t. The annual portions B_t can be equal portions, increasing/decreasing series or arbitrary. In the non-restricted scenario, B_T can be allocated to the planning period in the most economically efficient manner, where the only restriction is that the total pipe replacement costs in all years *T* cannot exceed B_T.

It is very important to note that for budgetary calculations pipe replacement costs are taken at their nominal values (including savings on economies of scale and roadwork alignments) and not at their present values.

Definition of solution objectives

The objectives of the solution are to schedule the replacement of candidate pipes during planning horizon *T*, so as to minimize the total cost, including replacement and break-related costs, subject to budget constraints. For practical purposes it is easier to use an alternative (but equivalent) method of minimising the total penalties. This minimisation is done while respecting budget constraints as well as maximising the usage of available budget. Three budget situations are considered namely, unconstrained, globally constrained and annually constrained. The globally constrained problem has a total budget B_T for the entire planning horizon, with no restriction on the distribution of this budget over the years. The annually constrained problem considers annual budgets B_t. Maximising budget usage means minimising the difference between the available budget(s) and the actual investment in pipe replacement.

Scheduling replacement using multi-objective GA

Genetic Algorithm (GA) is a search heuristic inspired by concepts of natural selection and survival of the fittest. Although GA concepts had been proposed earlier, they were popularised by Holland (1975) and his students at the University of Michigan, notably Goldberg (1989). GAs are well suited for searching discrete combinatorial spaces (continuous spaces will therefore need to be discretized). They have been widely applied to solve many types of problems in different scientific and engineering fields, such as scheduling, project planning, transportation, water networks design and maintenance and many others. The mathematical formulations of GAs are available in many text books (e.g., Goldberg, 1989) and will not elaborated in this paper. Traditional GAs are based on a so-called fitness function, whereby the (single) objective is to search for solutions that exhibit increasingly larger "fitness". A relatively recent development is the multi-objective GAs (MOGAs), which search for non-dominated solutions that offer trade-offs between the competing objectives.

In the field of water distribution, GAs have widely been used to optimise the renewal of water networks, where decision variables can include renewal dates, renewal alternatives (pipe diameter, renovation, etc.) and objective functions can include costs, reliability and/or hydraulic performance. GAs, e.g., Halhal et al. (1997), Savic and Walters (1997), were also coupled with hydraulic simulation programs, notably EPANET Rossman (2001) that serve as a tool to track conformance to hydraulic constraints. Dandy and Englehardt (2006) used MOGA to schedule pipe replacement (5-year time steps) on a double objective trade-off between maximizing network reliability and minimizing cost. Nafi *et al.* (2008) used Non-dominated Sorting Genetic Algorithm II (NSGA II – a type of MOGA) proposed by Deb et al. (2000), to address the pipe renewal scheduling problem while considering cost and hydraulic reliability. They used the proportional hazard model (*PHM*) to forecast future breaks and EPANET to account for network hydraulics. Non-dominated Sorting Genetic Algorithm (NSGA) has also been used by Prasad and Park (2004). Cheung *et al.* (2003) used Strength Pareto Evolutionary Algorithm (SPEA) coupled with EPANET for the design of water network by considering pipes and pumps as decision variables.

Encoding candidate solutions and computing fitness

A candidate solution is encoded by a chromosome with N genes, representing N decision variables, each corresponding to one of N candidate pipes. Each gene i contains an integer value t_i (t = 1, 2,…, T+1). Pipe i (i = 1, 2, …, N) is represented by the gene order in the chromosome (Figure 3). Note that candidate pipes that are scheduled for replacement in year T+1 represent all candidate pipes that will not be replaced in the current planning horizon.

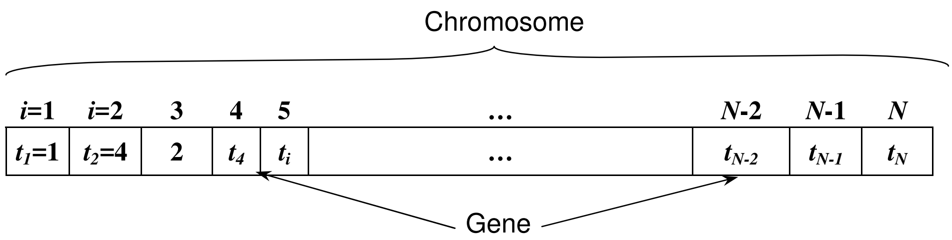

Figure 3.Encoding a renewal policy using a chromosome

Since there are two objectives, namely, minimize cost (or penalties) and maximize usage of available budget, two corresponding fitness values Obj_{cost} and Obj_{budget} need to be computed for a chromosome (candidate solution). Suppose that a candidate solution calls for the subset of pipes S_1 to be replaced in year 1, subset S_2 to be replaced in year 2, and so on, subsets S_t to be replaced in year t. Suppose further that S_t comprises s_t pipes. Obj_{cost} is computed in two parts as follows. First, the total penalty is computed, including savings due to quantity discount and coordination with scheduled roadwork but excluding contiguity savings (see equations 2 and 5 for notation).

$$TotPenalty = \sum_{t=1}^{T} \sum_{\forall i \in S_t} q_{i,t} = \sum_{t=1}^{T} \sum_{\forall i \in S_t} C_{i,t}^{tot} - C_{i,\hat{t}}^{tot}$$

where

$$C_{i,t}^{tot} = CR_{i,t} e^{-rt} + \sum_{j=1}^{t} k_{i,j} [(C_i^{rep} + C_i^{dir} + C_i^{wat}) e^{-rj} + C_i^{indir} + C_i^{soc}] \tag{9}$$

and

$$CR_{i,t} = M + (Cr_i \text{ - } \alpha_{i,t} D_{m,t} \text{ - } \beta_{i,t} p_i) l_i$$

In the second stage, contiguities are considered: if in year t the s_t pipes to be replaced are arranged in u_t contiguities, then the total savings on mobilization charges in year t are $M(s_t - u_t)$. Therefore total penalties now become

$$TotPenalty = \sum_{t=1}^{T}\left[\sum_{\forall i \in S_t} q_{i,t} - M(s_t - u_t)e^{-rt}\right] \tag{10}$$

Finally, we define the two objectives for the MOGA, i.e the (discounted) cost objective and the budget objective. The cost objective is simply

$$Obj_{\cos t} = TotPenalty \tag{11}$$

The exact nature of the budget objective, Obj_{budget}, depends on the problem explored. As stated earlier, three scenarios are explored, namely, unconstrained, globally constrained and annually constrained budgets. For the unconstrained problem, there is in fact no budget objective (the benefit of exploring this problem is discussed later). For the globally constrained problem, the budget objective expresses the difference (to be minimised) between total cash investment required for a renewal policy and the available budget. For the annually constrained problem the budget objective expresses the sum of the differences (to be minimised) between the annual cash investments required for a renewal policy and the available annual budgets. These scenarios are formulated as follows:

$$\text{for global budget:}$$
$$Obj_{budget} = B_T - \sum_{t=1}^{T}\left(\sum_{\forall i \in S_t}^{N} CR_{t,i} - M(s_t - u_t)\right)$$

$$\tag{12}$$

$$\text{For annual budgets:}$$
$$Obj_{budget} = \sum_{t=1}^{T}\left(b_t - \sum_{\forall i \in S_t}^{N} CR_{t,i} - M(s_t - u_t)\right)$$

Note that for budget calculations, investments are always computed as the cash (non discounted) value and with the consideration of all components of economies of scale, including coordination with scheduled roadwork, quantity and contiguity discounts.

Solution tools and parameters

Non Sorting Genetic Algorithm II (NSGA II) proposed by Deb et al.(2000) is used to identify feasible solutions with tradeoffs between competing objectives (i.e., minimise penalties and maximise budget usage). GANetXL Bicik et al. (2008), a prototype non-commercial program developed by the Centre for Water Systems (CWS) at the University of Exeter, UK and uses MS-Excel® as a platform was used in this study. A multipoint crossover operator was used to achieve greater diversity in the generated chromosomes. The probability of crossover between two chromosomes is denoted by P_c and the number of crossover points is determined by a random integer $1 \leq n_c \leq N$ generated by the software. A simple mutation operator with a probability of mutation P_m was used.

A solution that violates any budget constraint is in fact infeasible. In MOGA no infeasible solution should ever dominate a feasible solution. In order to achieve this, a high artificial penalty has to be levied on the fitness of an infeasible candidate. This penalty is referred to in this text as 'infeasibility penalty' to distinguish it from the penalty matrix described earlier. Two types of infeasibility penalties are used to impose budget constraints. In the global budget scenario, a infeasibility penalty is imposed on the candidate solution if total replacement cost exceeds B_T. In the annually restricted budget scenario, a infeasibility penalty is imposed on the candidate solution if any annual investment in year t exceeds annual budget b_t.

Example

For our example we used a section of a water distribution network that serves a community in Southern Ontario, Canada (Figure 4). Table 1 provides details about our sample network that comprised 152 cast iron pipes (total length 18,059 m), with diameters 150 to 200 mm, installed between 1951 and 1960 and with available breakage history for the years 1962 – 2003. A non-homogeneous Poisson-based model (I-WARP), capable of considering time-dependent covariates Kleiner and Rajani (2008, 2010) was used to forecast breakage rates. I-WARP was trained on breakage data of the 30-year period 1968-1997 and the trained model was used to forecast breakage rates for the 11 years between 1998-2008. Note that the planning horizon was considered to include the five years ($T = 5$) 1998 – 2002, and the forecast was therefore done for a period of $2T + 1$ years. The model forecasts $k_{i,t}$, which is the mean anticipated number of breaks in each pipe i, at each year t of the forecast period.

Clearly, such predictive models are inherently limited in predictive accuracy but in reality renewal planning must be done based on the best available information, which is invariably inaccurate.

Every pipe i for which C_{i,t^*}^{tot} was minimum at year $2T+1$ (i.e., its $\hat{t}_i$ was 2008) was removed from the list of candidate pipes considered for replacement in the planning horizon. Of the 152 pipes in the sub-network 23 pipes (total length 2,758 m) remained for replacement consideration. Details of these pipes are provided in Tables 1 and 2, and their respective locations are shown in Figure 4. Shaded pipes indicate candidates for renewal. Scheduled roadworks are marked by red triangles with their associated planned year. Contiguous pipes are marked bycircles (three in total).

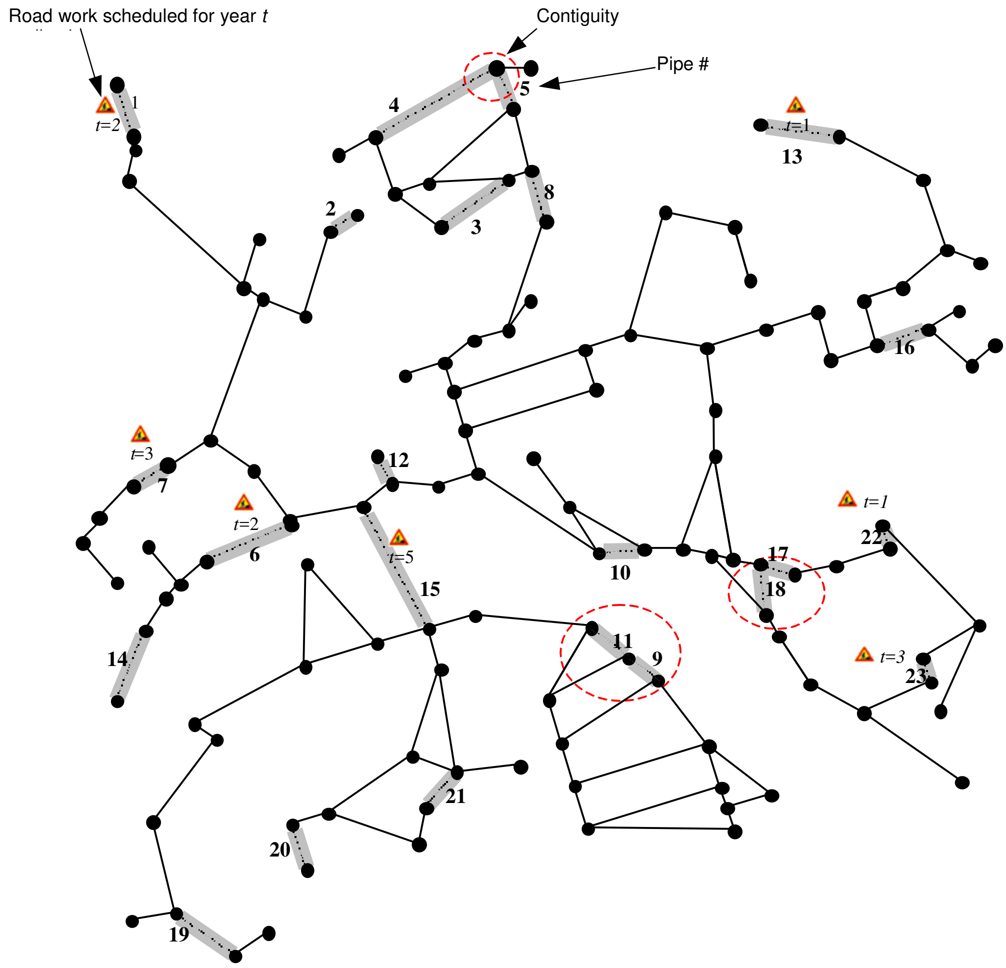

Figure 4. Layout (not to scale) of the sample network

Table 1. Pipes considered for replacement

ID	**Length (m)**	**Diam. (mm)**	**Zone**	*ID*	**Length (m)**	**Diam. (mm)**	**Zone**
1	170	150	1	**13**	203	150	1
2	64	150	2	**14**	201	150	3
3	166	150	1	**15**	284	150	2
4	339	150	1	**16**	108	150	2
5	85	150	1	**17**	37	150	3
6	181	150	3	**18**	101	150	3
7	82	150	1	**19**	146	150	2
8	103	150	1	**20**	93	150	2
9	76	150	2	**21**	6	150	2
10	88	150	2	**22**	47	200	2
11	94	150	2	**23**	50	200	3
12	62	150	2				

Table 2. Forecast of expected number of breaks, k_{ij} for $2T + 1$ years

Pipe	**Year *t***										
ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	0.19	0.19	0.20	0.20	0.20	0.20	0.21	0.21	0.21	0.21	0.22
2	0.14	0.14	0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.17
3	0.33	0.33	0.34	0.35	0.35	0.36	0.37	0.37	0.38	0.39	0.39
`4	1.01	1.03	1.05	1.08	1.10	1.12	1.14	1.16	1.19	1.21	1.23
5	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.15	0.15	0.15
6	0.31	0.32	0.32	0.33	0.34	0.34	0.35	0.35	0.36	0.37	0.37
7	0.16	0.17	0.17	0.17	0.17	0.18	0.18	0.18	0.19	0.19	0.19
8	0.16	0.16	0.16	0.17	0.17	0.17	0.17	0.18	0.18	0.18	0.19
9	0.19	0.19	0.20	0.20	0.20	0.21	0.21	0.21	0.21	0.22	0.22
10	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.13	0.13	0.13	0.13
11	0.14	0.14	0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.17
12	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.09
13	0.23	0.23	0.23	0.24	0.24	0.25	0.25	0.26	0.26	0.26	0.27
14	0.22	0.22	0.23	0.23	0.24	0.24	0.25	0.25	0.26	0.26	0.27
15	0.55	0.56	0.57	0.59	0.60	0.61	0.62	0.63	0.65	0.66	0.67
16	0.19	0.19	0.19	0.20	0.20	0.21	0.21	0.21	0.22	0.22	0.22
17	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.08	0.08
18	0.52	0.53	0.54	0.56	0.57	0.58	0.60	0.61	0.62	0.64	0.65
19	0.24	0.25	0.25	0.26	0.26	0.27	0.27	0.28	0.28	0.29	0.29
20	0.62	0.63	0.65	0.66	0.67	0.69	0.70	0.72	0.73	0.74	0.76
21	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
22	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
23	0.19	0.19	0.20	0.20	0.20	0.21	0.21	0.21	0.22	0.22	0.23

Table 3. Cost data

Item	Symbol	Unit	Value
Pipe replacement 150mm	Cr	\$/m	300
Pipe replacement 200mm	Cr	\$/m	350
Pipe repair (all diameters)	C_i^{rep}	\$/u	3,000
Discount rate	R	(%)	3.0
Minimum quantity for discount	L_m^{min}	(m)	500
Quantity for maximum discount	$L_m^{\max}$	(m)	1,500
Maximum quantity discount	$d_m^{\max}$	(%)	10
Cost saving due to roadwork	p_i	(%)	20
Cost of water loss due to failure	C_i^{wat}	(\$)	100

Table 4. Factors for cost assessment

	Zone 1	Zone 2	Zone 3
Impact cost factor	1	1.2	1.5
Social cost (\$)	1,000	3,000	5,000

Tables 3 and Table 4 provide economic data used in this example. Each pipe was assumed to be located in one of three zones, 1, 2, and 3 (Table 1), where each zone represents a different impact of pipe failure. Zone 1 represents low impact, e.g., industrial area; Zone 2 represents medium impact, e.g., residential area; and Zone 3 represents high impact, e.g., downtown area. Accordingly, each area is assigned different social cost of failure (Table 4) as well as an impact cost factor, used to multiply unit costs provided in Table 3. A discount rate of r =3%, is considered, which is in line with typical social discount rates (as opposed to financial discount rates) appropriate for public projects. For simplicity, indirect costs of pipe failure were taken as zero in this example.

As is indicated in Figure 4, roadworks are assumed to be scheduled at the locations of pipes 1, 6, 7, 13, 15, 22, 23 in years 2, 2, 3, 1, 5, 1, 3, respectively. Clearly, for every pipe i, penalty $q_{i,t} = 0$ when $t = \hat{t}_i$. Table 5 provides the penalty matrix Q, computed based on the predicted number of breaks (Table 2) and the cost data but does not yet considers economies of scale.

Table 5. Penalties matrix Q prior to economies of scale considerations.

Pipe	**Year *t***									
ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	5,504	4,799	4,132	3,501	2,905	2,343	1,813	1,315	848	410

2	0	177	378	601	847	1,115	1,403	1,712	2,040	2,388
3	245	126	47	6	0	29	91	185	309	463
4	0	1,124	2,332	3,622	4,988	6,428	7,938	9,514	11,154	12,854
5	1,414	1,195	995	813	649	501	371	256	156	71
6	0	169	427	770	1,197	1,706	2,294	2,959	3,700	4,514
7	90	43	14	0	2	19	51	96	155	226
8	1,551	1,306	1,083	881	699	538	395	270	164	74
9	0	365	753	1,164	1,597	2,052	2,528	3,023	3,539	4,073
10	1,137	912	713	541	394	271	172	96	43	11
11	342	210	111	43	7	0	22	73	151	255
12	1,123	933	762	608	472	354	252	166	96	40
13	6,399	5,560	4,770	4,026	3,328	2,673	2,060	1,488	955	459
14	4,352	3,499	2,745	2,089	1,527	1,056	675	382	173	46
15	0	370	850	1,437	2,126	2,914	3,800	4,779	5,849	7,008
16	0	13	64	153	278	439	633	861	1,122	1,413
17	0	63	140	232	338	459	592	739	899	1,071
18	0	2,834	5,768	8,801	11,929	15,151	18,465	21,869	25,360	28,937
19	52	0	2	55	159	311	510	756	1,046	1,379
20	0	2,752	5,562	8,427	11,347	14,319	17,341	20,412	23,532	26,697
21	0	92	185	278	373	468	564	660	757	855
22	1,043	874	720	581	458	348	252	170	101	44
23	0	754	1,544	2,369	3,228	4,120	5,045	6,001	6,989	8,007

Shaded cells denote $\hat{t}_i$

Baseline solution

For convenience we define a baseline solution (policy) where each pipe i, with penalty $q_{i,t} = 0$ is replaced at year t provided $t \leq T$. From Table 5 it is clear that the baseline solution comprises all pipes except pipes 1, 5, 8, 10, 11, 12, 13, 14 and 22. The renewal policy obtained for the baseline solution is represented by the chromosome depicted in Figure 5. Recall that in our chromosome representation, pipes that are scheduled to be replaced in year T+1 (i.e., years 6) represent pipes that will not be replaced in this renewal policy but rather in the next planning period.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
6	1	5	1	6	1	4	6	1	6	6	6	6	6	1	1	1	1	2	1	1	6	1

Figure 5. Chromosome representation of the baseline solution

This baseline solution will be used as a reference point for comparing optimised solutions. Consequently its quality, in terms of cost and investment budget, need to be computed, including all economies of scale considerations. Table 6 provides the details of the baseline solution, with mobilization cost taken as M = \$2000.

Table 6. Details of the baseline policy

	Year t						**Total**
	1	2	3	4	5	*Next T*	
Total length to replace $\sum l_i$ (m)	1,339	146	0	82	166	1,052	2,785
Total length to replace $\sum l_i$ (%)	48%	5%	0%	3%	6%	38%	100%
# of pipes to replace n_t	11	1	0	1	1	9	23
# of alignments with roadwork	0	0	0	0	0		0
Savings due to roadwork alignment ($)	0	0	0	0	0		0
# of contiguities U_t	1	0	0	0	0		1
Savings due to contiguities ($)	2,000	0	0	0	0		2,000
Saving due to quantity discount ($)	39,635	0	0	0	0		39,635
Total savings ($)	41,635	0	0	0	0		41,635
Expected # breaks avoided (relative to do nothing) during T	16.05	0.77	0	0.79	0.71	0	18.32
Total penalty due to replacement shifting ($)	0	0	0	0	0	0	0
Total investment in replacement ($)	454,818	52,571	0	24,507	49,884		581,780

Note that among the 14 pipes scheduled for replacement in the baseline policy one contiguity exists in year 1 (pipes #17 and 18). Also the baseline solution does not benefit from any alignment with scheduled roadwork. A quantity discount can be applied in year 1 due to the total length of pipe scheduled for replacement.

Optimised solution with no budget constraint

We applied the MOGA without budget constraints, i.e., to minimise total (discounted) penalty. The MOGA was applied with a population of 200 chromosomes (candidate policies) and 500 generations, a multipoint crossover with probability $P_c = 0.95$ and simple mutation with probability $P_m = 0.05$. Renewal policy was optimized with respect to all economies of scale savings, including contiguity (mobilization cost M = $2,000) roadwork coordination and quantity discount. Figure 6 illustrates the optimized Pareto front and how it relates (dominates) the baseline solution (for the same investment level the optimized solution will save approximately $50K in discounted costs. Note that this Pareto front in fact provides the optimal (or near optimal) renewal policy for any given level of total budget B_t.

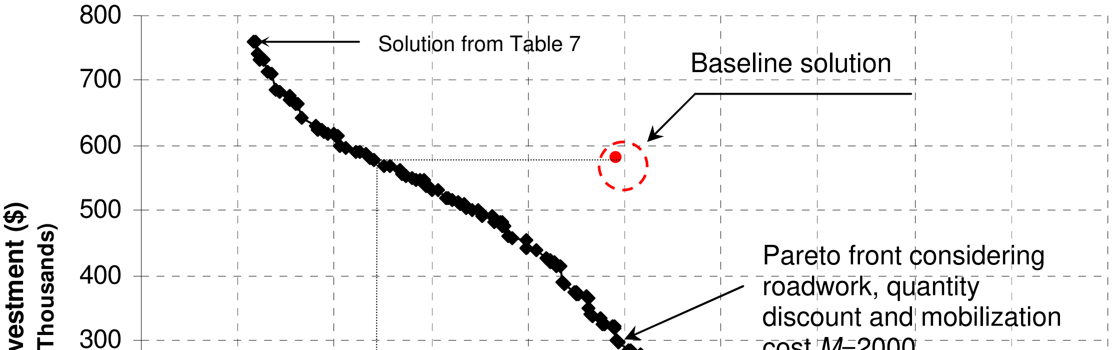

Figure 6. Pareto-front of optimised (unconstrained) solutions

Table 7 provides details on the costs involved in a selected policy from the optimised Pareto front, and Figure 7 illustrates, using arrows, how replacement schedules were shifted from the baseline solution to the optimised solution, to take advantage of the various economies of scale discounts (recall that when a pipe is scheduled for replacement at years 6 it means that its replacement is deferred to the next planning horizon). For example, renewal of pipe 1 shifted from year 6 to year 2 to benefit from discount due to harmonisation with scheduled roadwork. Pipes 5, 8, 10, 11, 12, 13 and 22 shifted from year 6 to year 1 to benefit from quantity discount as well as mobilisation savings due to contiguity (pipes 5 and 11) and harmonisation with scheduled roadwork (pipes 13 and 22); and so forth. This optimised policy sees the replacement of 22 pipes (2,583m length – see Table 5) compared to 14 pipes (1,733 m length –Table 4) in the baseline policy with renewal investments of $760,553 compared to $581,780. The optimized solution added 852 m of pipe replacement at an additional cost of $178,773 (marginal cost of less than $210 per meter – compared to the average cost of $300/m for 6” pipe).

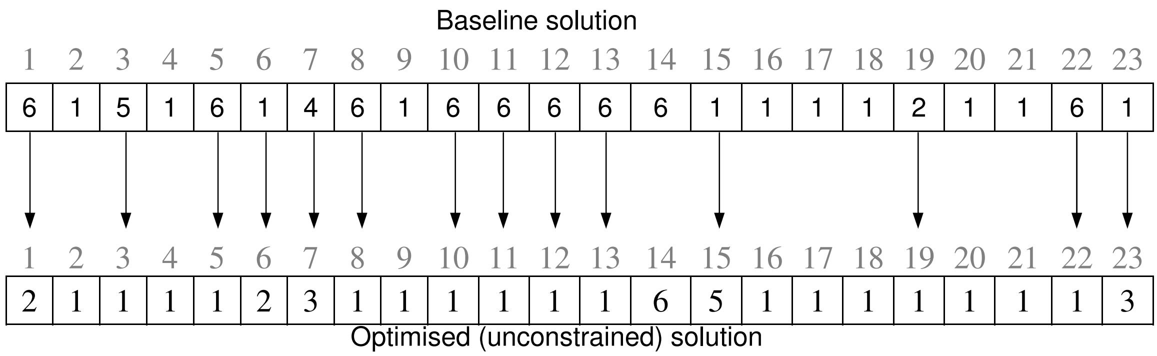

Figure 7. Comparison between baseline and the optimised solution from Table 7.

Table 7. Details of a renewal policy (identified in Fig 6) from the optimised Pareto front

	Year t						**Total**
	1	2	3	4	5	*Next T*	
Total length to replace $\sum l_i$ (m)	1,818	351	132	0	284	201	2,785
Total length to replace $\sum l_i$ (%)	65%	13%	5%	0%	10%	7%	100%
# of pipes to replace n_t	17	2	2	0	1	1	23
# of alignments with roadwork	2	2	2	0	1		7
Savings due to roadwork alignment ($)	16,111	26,502	10,151	0	20,424		73,188
# of contiguities U_t	3	0	0	0	0		3
Savings due to contiguities ($)	6,000	0	0	0	0		6,000
Saving due to quantity discount ($)	59,621	0	0	0	0		59,621
Total savings ($)	81,732	26,502	10,151	0	20,424		138,809
Expected # breaks avoided (relative to do nothing) during T	18.24	1.59	0.74	0	1.21		21.78
Total penalty due to replacement shifting ($)	13,307	4,968	1,557	0	2,126	0	21,958
Total investment in replacement ($)	532,241	106,009	40,606	0	81,697		760,553

Optimised solutions with budget constraints

In order to examine the impact of various budget schemes, we set the global budget to B_T = \$760,553, which is the highest investment obtained earlier for the unconstrained problem. This ensured that the policy constrained by global budget will be at least as good as the unconstrained policy, thus guaranteeing full benefits of economies of scale discounts. We examined three schemes of annual budget constraints, whose total amounted to B_T, as is depicted in Table 8. Figure 8 illustrates the results with M = \$2000 (note that the data points in Figure 8 represent discrete solutions and the lines connecting them are provided only as a visual aid to highlight the Pareto front that is comprised of these data points. The same holds for Figures 6, 9, and 11).

Table 8. Annual budget constraints

Annual constraint	*Year t* 1	2	3	4	5
Constant	$152,111	$152,111	$152,111	$152,111	$152,111
Increase 10 %/year	$124,577	$137,034	$150,738	$165,812	$182,393
Decrease 10 %/year	$182,393	$165,812	$150,738	$137,034	$124,577

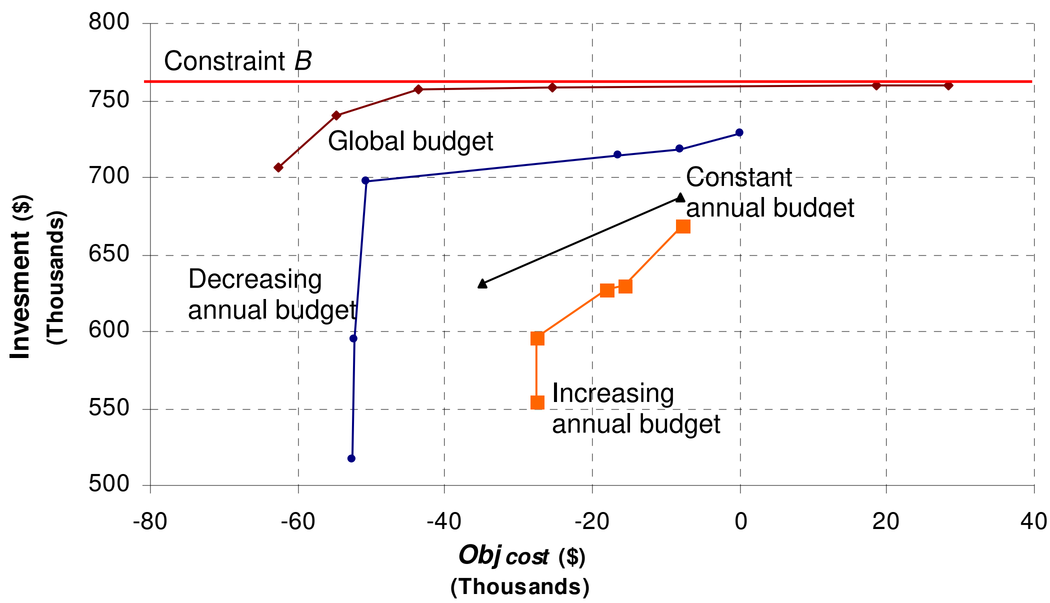

Figure 8. Pareto fronts for renewal planning under budget constraints

The following observations are noted:

- Global budget clearly dominates, as expected, all annual budget schemes.
- Among the different annual budget schemes, the decreasing scheme dominates the others because a large portion of the pipes in the example are expected to be replaced at year 1 because of anticipated increasing failure costs and because of economies of scale benefits, including scheduled roadwork, contiguities and quantity discounts.

- The constant annual budget scheme dominates the increasing annual budget for the very same reason that the decreasing annual budget is expected to dominate the others, i.e., the favoured policy is the one that allows for more pipe replacements earlier in the planning period.
- While the global budget scheme utilizes (nearly) the entire available budget (approx. $760K to maximize discounted cost savings (about $-118K), the annual budget schemes, because of inefficiencies in the time-allocation of investment, do not use the entire available budget (only about $510K-540K) to achieve their respective maximal cost savings (which at about $57K are of course inferior to the cost savings achieved by the global budget scheme. In fact forcing the annual budget scheme to use more of the available budget degrades their ability to achieve cost savings.

Sensitivity analysis: impact of discount rate and quantity discount

We tested the case of the unconstrained problem (Case C) with three different values of discount rate, r = 3%, 6% and 9%. Clearly, in the approach proposed here, discount rates directly affect only the (discounted) cost objective and not the budget (or investment) objective. Results are illustrated in Figure 9 and Figure 10. In general, higher discount rates will tend to defer cash outlays. In this case study the higher discount rates caused many pipe replacements to be deferred to the next planning horizon. Consequently maximum investments on the Pareto fronts were $760,553, $617,628 and $183,736 for discount rate of 3%, 6% and 9%, respectively.

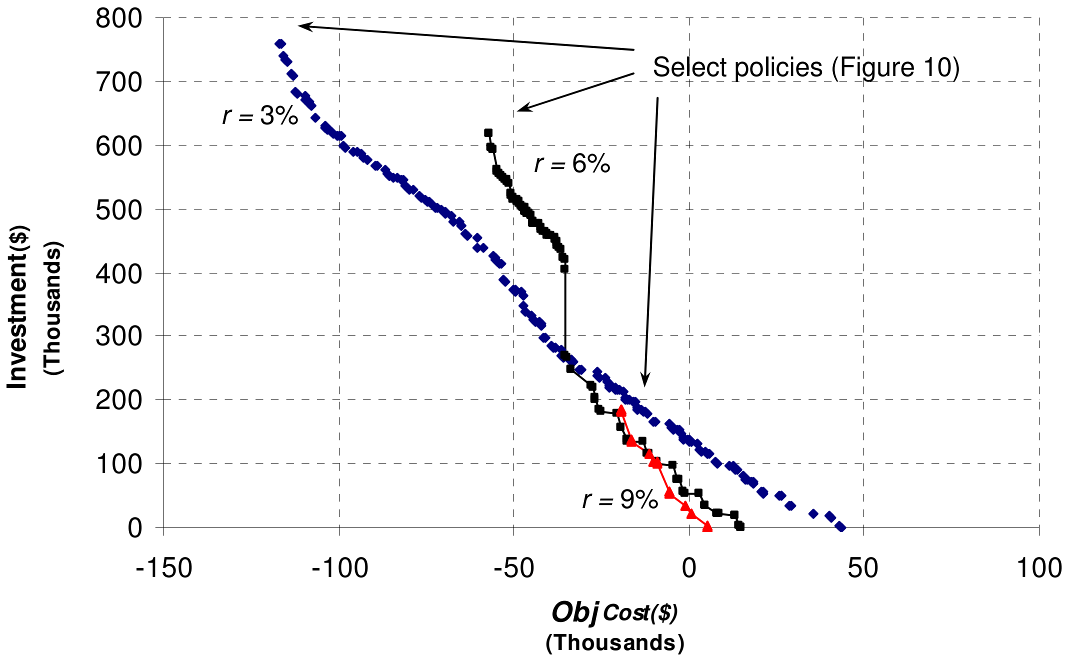

Figure 9. The impact of variation of discount rate value on Pareto front

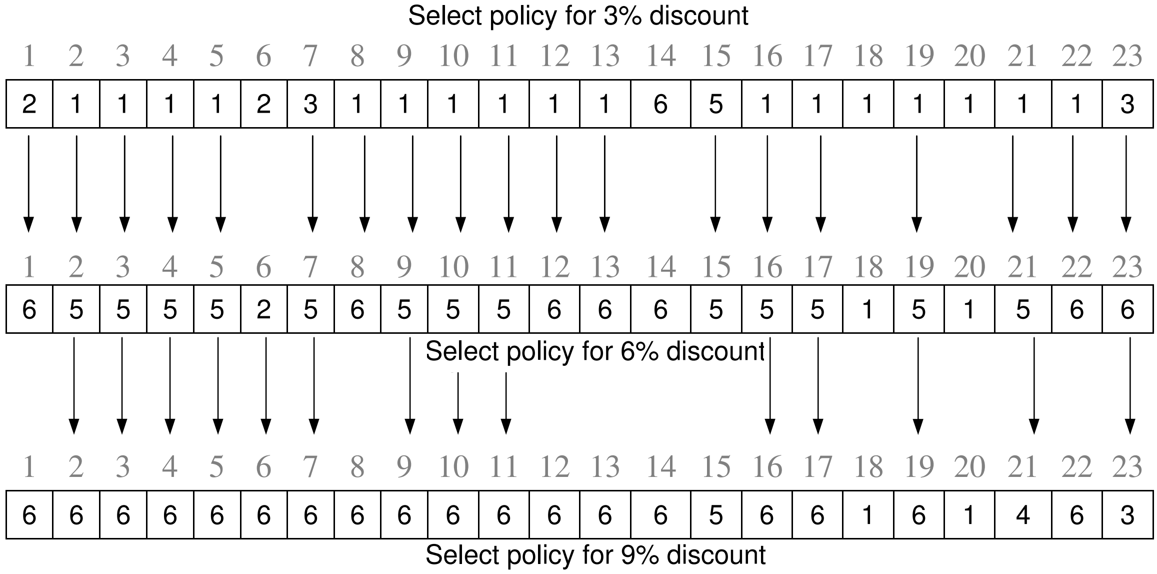

Figure 10. Comparison between select renewal policies with varying discount rates.

Figure 10 illustrates that the number of pipes to be replaced in policies selected from the three Pareto fronts were 22, 16 and 5 for discount rates of 3%, 6% and 9% respectively.

In this same manner, we tested the unconstrained problem (Case C) with three different values of maximum quantity discount $d_m^{\max}$ = 0%, 5% and 10%. Results are illustrated in Figure 11 and Figure 12. At low investment levels (i.e., when few pipes are replaced) quantity discount value has no impact because too few pipes are replaced to enjoy the benefits of such a discount.

In our case study, the investment threshold, below which quantity discount does not matter, appears to be approximately \$350,000. On the contrary as expected, high quantity discounts encourage high investments above an investment threshold of about \$400,000.

Policies selected from the three Pareto fronts are compared, as shown in Figure 12. At $d_m^{\max}$ of 0%, 5%, and 10% the total number of pipes to be replaced are 10 (1,562m, \$503,483), 20 (2,527m, \$795,809) and 22 (2,585m, \$760,553), respectively (with mean pipe costs of \$322/m, \$315/m and \$294/m). It is also interesting to note that at $d_m^{\max}$ =5%, maximum quantity discount was realised at year 2, while at $d_m^{\max}$ =10%, maximum quantity discount was realised at year 1.

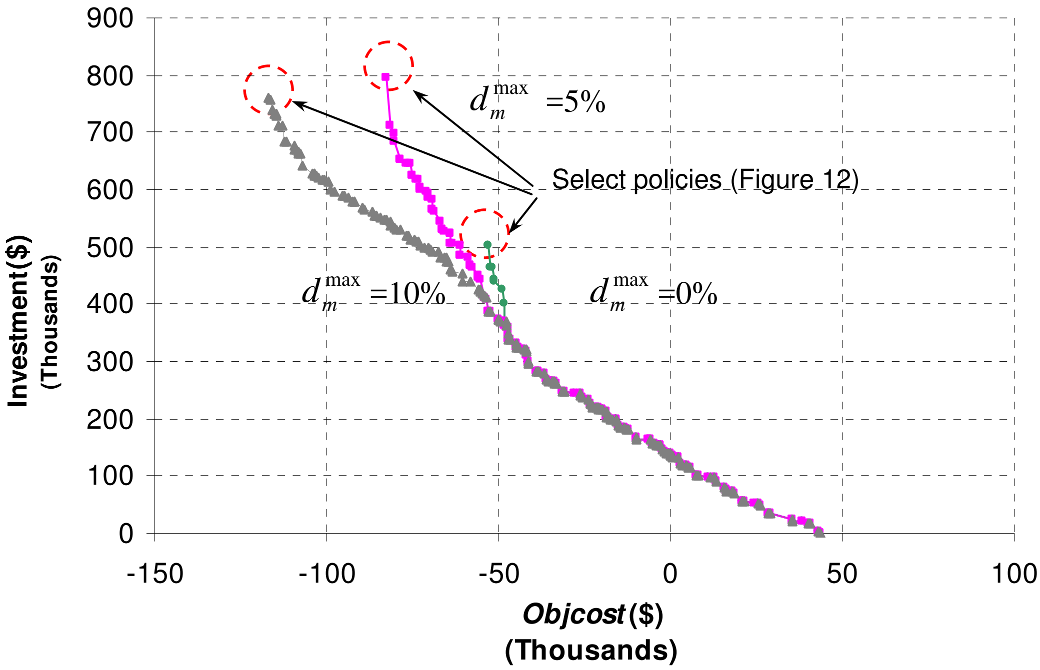

Figure 11. The impact of variation of maximum quantity rate value on Pareto front.

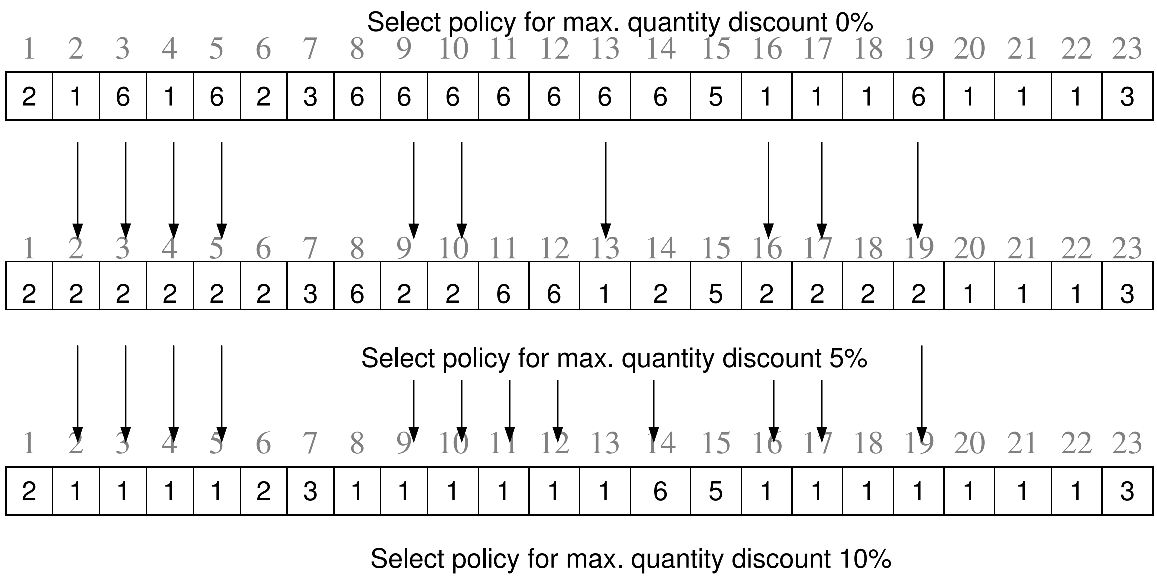

Figure 12. Comparison between select renewal policies with varying quantity discounts.

Discussion

The consideration of economies of scale and infrastructure adjacency in planning the renewal of water mains has so far not received much attention in the literature. The challenges can be both conceptual and computational. Conceptual challenges, such as contiguity considerations can be overcome by obtaining a good handle on the manner with which contractors price projects. It has been the experience of the authors that contractor pricing considerations can vary substantially between individual contractors. Moreover, discussions with contractors in Canada seem to suggest that they are not always consistent with the factors they consider to price a project. Consequently, simplifying assumptions and rationalizations are often necessary for any modeling effort. Computational challenges are due to the fact that economies of scale typically exacerbate the non-linearity of a problem that is already non-linear. Furthermore, some phenomena are discrete (e.g., contiguity) rather than continuous. In this research, we chose to address these computational challenges by transforming the problem to a discrete one and solving it with MOGA. In order to reduce the solution space to a manageable one, we assumed that a five-year (or so) planning horizon (T) is a reasonable and practical period for a water utility to plan the replacement of individual pipes. However, by initially considering a period of $2T$+1 (and subject to assumptions about breakage patterns of pipes), we ensure that this short planning horizon of duration T will not result in the loss of feasible and potentially optimal solutions.

We examined three types of economies of scale and infrastructure adjacency, namely quantity discount, contiguity discount (savings on mobilization costs) and harmonization of pipe replacement with known scheduled roadwork. The impact on the costs and budget of economies of scale and infrastructure adjacency was demonstrated with the help of a relatively simple example. This example comprised a real network and real anticipated (mean) numbers of pipes breaks, however, costs and roadwork, while realistic, were mostly assumed.

The moderately simple example is helpful in that it is not trivial yet simple enough to gain an intuitive understanding of the expected results. It is therefore reassuring that the proposed approach identified solutions that appear to be near optimal. Specific numerical results are not important here because they can vary with different assumptions about mobilization costs, roadwork savings, etc. What is important is that the information presented in Figure 8 can be a solid basis for making sound decisions about budgeting pipe renewal as well as pipe maintenance (based on anticipated breaks). Moreover, this approach can ultimately be extended so as to consider the schedule of pipe works and roadwork simultaneously (rather than use roadwork as a given constraint) to achieve an even higher cost effectiveness.

Finally, it should be noted that a fully practical decision support system often requires additional information that is not readily available at s single pipe resolution. For example, pipe replacement is often accompanied by the replacement of service connections, hydrants, valves, and other appurtenances attached to this pipe. Information about the condition and cost of these items should be considered. Further, re-pavement works may have different unit cost, depending on the type of road. Equation (2) was formulated to accommodate such data by assigning pipe-specific replacement costs (pipe costs all carry index *i*), but for simplicity the example did not address these data.

Concluding remarks

The approach described here, for planning the replacement of individual water mains, is currently limited to the consideration of structural resiliency (i.e., breakage frequency) of pipes and the economics of their replacement. In reality, other factors should also be considered as well, such as hydraulics (including the consideration of larger diameter replacement pipes), reliability, etc. More work is required to incorporate additional considerations into this approach.

The assumptions about cost-contiguity implications are rather simple and may be overly simplified. For example, if 100 pipes are (spread out but) contiguous does this mean that 99 mobilisation costs would be saved, or should there be a realistic spatial limit to the extent of a contiguity? Further, if two water mains are separated by a third, short (say 20 m) pipe, will they not save mobilization costs? It seems that a spatial element may be required to refine the consideration of mobilization cost savings.

Finally, the residual value of the network at the end of the planning horizon was not considered in comparing renewal policies. . While it is clear that a policy comprising more pipe replacements yields a newer (and presumably higher value) network at the end of a planning horizon, it is not clear how this residual value might be monetised (e.g., replacement value, depreciated historical value or expected life-cycle maintenance cash flows) and incorporated in penalty matrix or perhaps considered as an additional objective in this multi-objective problem.

Notation

a Annual budget increase.

$\alpha_{i,t}$ Binary variable for the type of material of the pipe *i*, in year *t*.

B_T Global Budget on the horizon planning *T*.

b_t Annual budget constraint in year t (t = 1, 2,…T).

$\beta_{i,t}$ Binary variable for the roadwork scheduling for the pipe i in year t.

C_i^{rep} Cost of failure repair in pipe i.

C_i^{dir} Cost of expected direct damage at failure in pipe i.

C_i^{indir} Cost of indirect damage at failure in pipe i.

C_i^{wat} : Cost of water loss at failure in pipe i.

C_i^{soc} : Social cost of failure in pipe i.

$C_{i,t}^{tot}$: Total cost associated with pipe i at year t.

Cr_i Pipe i replacement cost ($/m).

Cf_i: Total cost of failure in pipe i ($).

$CR_{i,t}$ Cost of replacing pipe i at year t ($).

$\Delta Cf_{i,t}$: Expected discounted cost of failure of pipe i at year t.

$\Delta CR_{i,t}$ Marginal savings in deferring replacement of pipe i from year t to $t+1$.

$D_{t,m}$ Quantity discount for the replacement of pipes of material m in year t.

$d_m^{\max}$ Maximum quantity discount available for pipe material m.

Obj_{cost} Objective function assessing the total penalties for a given renewal policy.

Obj_{budget} Objective function assessing the total investment for a given renewal policy.

$k_{i,t}$ Forecasted expected number of breaks in pipe i at year t.

l_i Length of pipe i.

$L_m^{\max}$ Total length of pipes of material m for which maximum quantity discount is available.

$L_m^{\min}$ Total length of pipes of material m for which minimum quantity discount is available.

$L_{t,m}$ Total length of pipes of material m to be replaced in year t (for quantity discount calculations).

M Mobilization cost.

n_c Number of crossover points.

n_t Number of pipes renewed in year *t*.

P_c Probability of crossover.

P_m Probability of mutation.

p_i Discount when replacement of pipe *i* is coordinated withroadwork.

$q_{i,t}$ Penalty for the renewal the pipe *i* in year *t* (members of $\boldsymbol{Q}$).

Q Penalty matrix.

r Social discount rate.

s_t Number of pipes to renew in year *t* (for contiguity calculations).

T Planning horizon.

t_i Renewal year for pipe *i*.

$\hat{t}_i$ Year when $C_{i,t}^{tot}$ is the smallest in the analysis time window $2T+1$ years.

t^* Year when $C_{i,t}^{tot}$ is minimum.

u_t Number of contiguities in year *t*.

$V_{t,m}$ Number of pipes of the same material *m*, considered for renewal in year *t*.

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