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A COMPREHENSIVE APPROACH TO LONG AND SHORT TERM PLANNING OF WATER MAIN RENEWAL

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Abstract

Efficient renewal planning of water mains requires the consideration of the long term deterioration of their structural resiliency, their deteriorating hydraulic capacity and their life-cycle costs. Cost of pipe replacement can be significantly affected by economies of scale and by coordinating pipe replacement with adjacent infrastructure work such as roads, sewers, etc. The simultaneous consideration of all these factors at a single pipe planning resolution is computationally prohibitive due to vast dimensionality. In this paper we present a comprehensive approach that considers these factors in two stages. In the first stage, the long-term deterioration of both the structural resiliency and hydraulic capacity of water mains are explored, along with the consequences of failure and renewal cost, to produce a list of candidate pipes to be considered for renewal in the short-term. In the second stage, these candidate pipes are examined in more detail, including economies of scale and adjacent infrastructure consideration, to produce the best candidates for immediate and near-term action.

Key words

long term planning, short term planning, water main renewal, hydraulic capacity, genetic algorithm, economies of scale, adjacent infrastructure.

1. INTRODUCTION

The optimal scheduling of pipe renewal has received the attention of numerous researchers over the last 2-3 decades. Methods have been proposed, e.g., [1], [2], [3], [4] among others, for long-term, high level planning for pipe cohort renewal, as well as for short-term, low-level planning at an individual pipe resolution, e.g., [5], [6], [7], [8] to name but a few. The efficient renewal planning of pipes in water distribution networks requires the simultaneous consideration of the long term deterioration of their structural resiliency as well as their deteriorating hydraulic capacity (throughout the planning period) coupled with their life-cycle costs. Moreover, the cost of pipe replacement can be significantly affected by economies of scale and by coordinating pipe replacement with adjacent infrastructure work such as roads, sewers, etc. The simultaneous consideration of all these factors at a single pipe planning resolution is computationally prohibitive due to the vast dimensionality of the solution space. Furthermore, there is little benefit in the long-term consideration of issues such as coordination with adjacent infrastructure works, when these works are in fact known with an acceptable level certainty only in the short term.

In this paper we present a comprehensive approach that considers these factors in two stages. In the first stage, the long-term deterioration of both the structural resiliency and hydraulic capacity of water mains are explored, along with the consequences of failure and renewal cost, to produce a list of candidate pipes to be considered for renewal in the short-term. In the second stage, these candidate pipes are examined in more detail, including economies of scale and adjacent infrastructure consideration, to produce the best candidates for immediate and near-term action.

The approach presented here is largely based on past work of the authors. Due to space limitations, the descriptions of this past work is rather terse and the interested reader is encouraged to examine this work in more details through the provided references.

2. LONG-TERM PLANNING

2.1 General concept

The long-term planning stage is predicated on the approach proposed by [8] (also presented in [9]), where the deterioration over time of both the structural integrity and the hydraulic capacity of every pipe in the water distribution network is explicitly and simultaneously considered. A pipe cost function accounts for an infinite time stream of costs, comprising the present value of breakage consequences and renewal costs. Figure 1 illustrates this concept, where T^f denotes time of first replacement and T^c denotes the duration of subsequent (perpetual) replacement cycles that are assumed, as first approximation, to be identical.

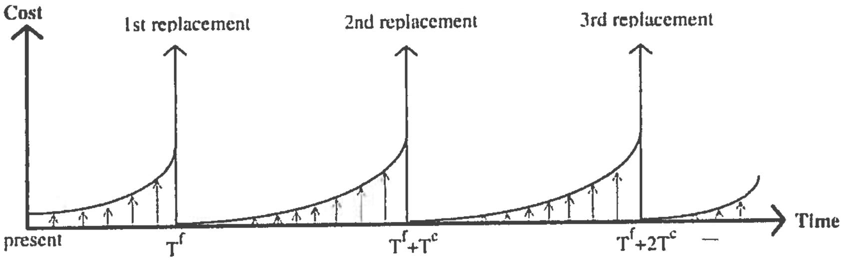

Figure 1. Stream of costs (steady state) associated with a single pipe [9]

It is shown in [8] that a cycle duration T^{**} can be found, such that the sum of all costs cycles from T^f to infinity is minimised. Subsequently, a time T^* can be found, such that the sum of all costs from the present to infinity is minimised. Further, [8] adopted the approach proposed by [10] to represent the hydraulic capacity deterioration of water mains by the age-dependent (logarithmic) reduction in the Hazen-Williams hydraulic conductivity coefficient.

An optimised pipe renewal process was proposed [8]. The decision variables are (1) the type of rehabilitation alternative to implement (replace with same diameter pipe, replace with larger diameter pipe, reline, don't renew) and (2) the time of its implementation, for every pipe in the distribution network. The constraints are (1) conservation of mass, (2) conservation of energy, and (3) minimum nodal residual supply pressure; where all constraints are imposed though all time steps in a pre-defined planning period (typically 30-50 years). A multistage procedure, based on dynamic programming and partial enumeration was proposed to obtain results. This procedure, however, is efficient only for very small network, due to the vast dimensionality. In the current adaptation of this approach, a new, genetic algorithm (GA)-based solution process is employed. The output of the procedure provides, for each pipe in an existing network, the rehabilitation alternative and its implementation timing, so as to minimize the present value of the total life-cycle costs of all pipes in the network. The pipes found through this approach to have the earliest renewal schedule are the natural candidates for consideration in the second stage, where short-term renewal planning is carried out.

2.2 Adaptation to current approach

Despite the fact that the cost function considers perpetual life-cycle costs to infinity, a planning period has to be defined over which hydraulic adequacy is ensured. Consequently, the residual value of the network at the end of the planning period has to be considered, lest the optimisation process introduces bias against pipe renewal, especially when the renewal takes place towards the end of the planning period. This issue is discussed in [8] but is not explicitly considered. In the current adaptation a simplified approach was used, whereby T^{**} was used as a first approximation to the mean life expectancy of a pipe. Thus for example, if it is found that for a certain replacement for pipe i, $T_i^{**} = 100$ years, and if pipe i was scheduled to be replaced, say 20 years before the end of the planning period, then at the end of the planning period the residual value of this pipe is considered to be equal to the present value of 80% (= (100 - 20) / 100) of its replacement value.

In order to reduce the dimensionality of the problem, the current approach implements the long-term phase with time steps of 5 years, where the hydraulic constrained is examined at the end of each time step. For simplicity (and because of the limitation of the GA program used), the example presented in this paper for demonstration encompasses only two renewal alternatives, namely replace pipe with same diameter pipe or continue to repair without replacement. The pipe that through the long-term optimisation were scheduled for replacement in the first or second time step (i.e., scheduled to be replaced in the first 10 years) are considered as candidates for the subsequent short-term planning, that includes also economies of scale and coordination with adjacent infrastructure works.

3. SHORT-TERM PLANNING

The short-term renewal planning stage is based on the approach proposed by [11]. In this approach, multi-objective genetic algorithm (MOGA) is used to identify pipes among a set of candidates and schedule their renewal so as to minimise the total discounted cost associated with their anticipated failure and their renewal. In this stage, typically 5-10 year long, economies of scale are considered, as well as coordination of pipe renewal with known scheduled work on adjacent infrastructure. The short-term planning stage produces a Pareto, non-inferior set of strategies. Each strategy comprises a list of pipes to renew in the short-term, for a given budget level. Unlike [11], which did not consider hydraulics, in this adaptation minimum nodal pressure constraint is enforced, through the use of penalty in the search process. In both the long and the short-term planning processes minimum nodal pressure is enforced using EPANET [12].

4. EXAMPLE

4.1 Data and assumptions

The network used by [4] was used here, with minor necessary modifications, to demonstrate the new concept (Figure 2). The network includes a total of 147 pipes cast iron pipes, of lengths ranging from about 6 to 540 meters (total length ~22,300m), of which 143 (~22,020m) are 150 mm in diameter and 4 (~280m) are 200 mm. The ages of the pipes range between 37 and 41 years. Breakage rate increase parameters for each pipe were discerned from available breakage history (From 1962 to 2003). Parameters for hydraulic capacity deterioration rates were not available, therefore a reasonable range of values was assumed and values were selected at random from this range and assigned to the individual existing pipes. Replacement pipes were assumed to be ductile iron, for which reasonable values were assumed for breakage parameters (initial breakage rate of 5 breaks/100km/year and exponential increase rate of 0.0178/year). The hydraulic capacity deterioration rate of each replacement pipe was assumed to be identical to that of the existing pipe to be replaced.

Table 1 provides cost data used for this example. Each pipe was assumed to be located in one of three zones, 1, 2, and 3, where each zone represents a different impact of pipe failure. Correspondingly, the cost of pipe failure in Zone 1 was taken as base cost (Table 1), for Zones 2 and 3 this base cost was multiplied by a factor of 1.2 and 1.5 respectively. The long-term planning period was taken as 30 years and discount rate was taken as 0.03, for both long and short-term planning.

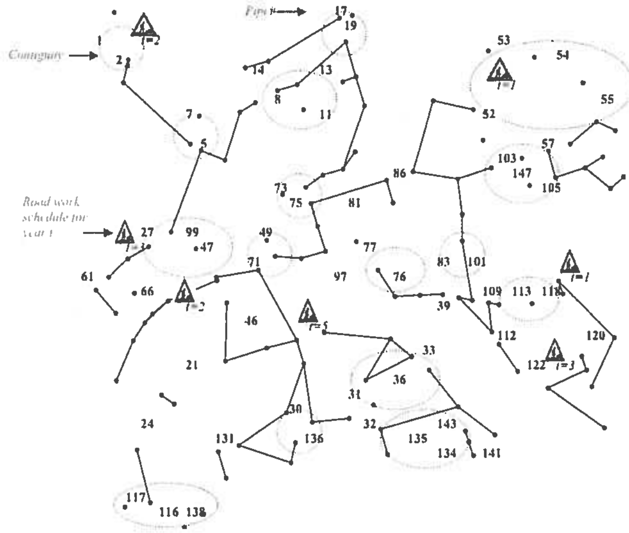

Figure 2. Layout (not to scale) of example network.

Table 1. Cost data.

Item	Unit	Value
Pipe replacement 150mm	$/m	300
Pipe replacement 200mm	$/m	350
Pipe repair (base, 150 & 200mm)	$/u	3,000
Discount rate	(%)	3.0
Minimum quantity for discount	(m)	500
Quantity for maximum discount	(m)	1,500
Maximum quantity discount	(%)	10
Cost saving due to roadwork	(%)	20
Mobilisation cost	$/u	2,000
Cost of water loss due to failure	($)	100

4.2 Long-term planning

The long-term planning phase was applied to all pipes i (i = 1,2,...147) in the network. First all values T_i^{**} were computed for the existing pipes and replacement pipes. The values are the same, because T_i^{**} indicates the optimal renewal date according to periodic renewal. Because T^{**} values depend on the various breakage and installation costs, they vary among the replacement pipes between 230 and 250 years (the smaller values correspond to those pipes whose failure history indicated high ageing rates (i.e., fast increase in break rate).. It is noted that the replacement pipes have no breakage history therefore they were all assumed to have the same ageing rate, as noted earlier. Recall that T^{**} values are used to calculate the residual value of the network at the end of the long-term planning period.

The optimal long-term scheduling scheme was searched by a Simple Genetic Algorithm (SGA) implemented in VBA-Excel, whereby feasible scheduling schemes are first generated at random, and subsequently the best fit (i.e., the lowest cost) schemes have a higher probability of producing the next generation of feasible schemes. Each scheduling scheme is examined for compliance with the minimum nodal pressure constraint in each of the time steps in the planning

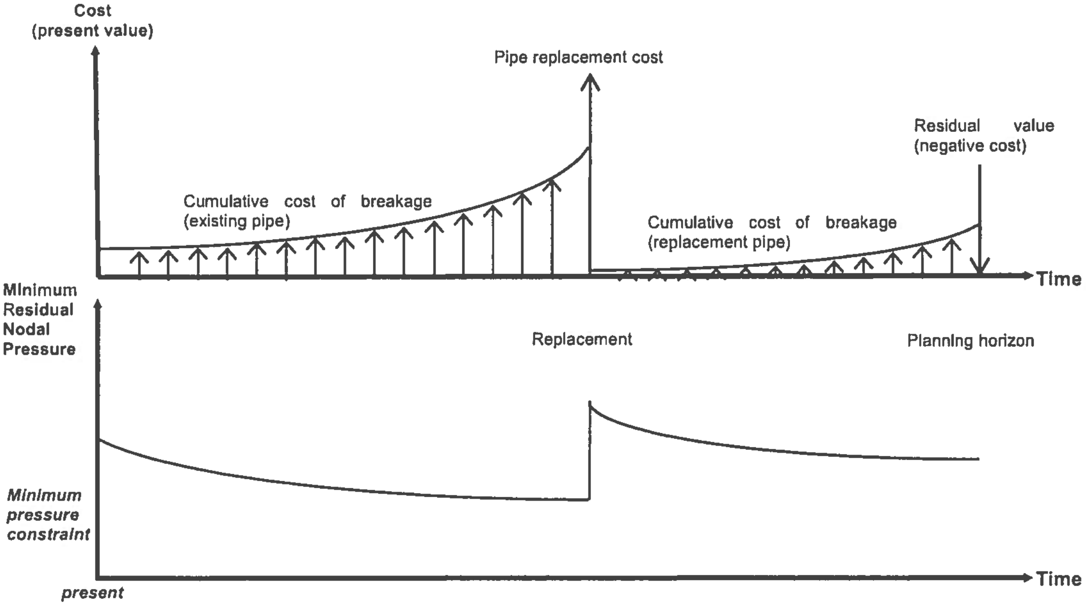

Figure 3. Example of feasible scheduling scheme

Table 2. Results of long-term planning phase – optimal scheduling scheme (cost values rounded to 000).

	Time step								
	0[1]	1	2	3	4	5	6	7[2]	Total
# pipes replaced	13	26	21	24	18	17	13	15	147
Length (m)	1,656	3,900	3,030	3,934	2,583	3,003	1,561	2,633	22,300
Min. pressure (m)	20.03	20.01	20.24	20.10	20.09	20.08	20.07	-	20.00
Maintenance, pre[3]	441,032	239,858	116,641	126,074	139,954	161,059	95,433	-	6,248,932
Maintenance, post[4]	0	278	755	944	1,115	1,090	1,058	-	16,279
Replacement cost	498,557	1,241,256	893,543	1,222,804	805,320	965,518	470,214	-	6,097,211

[1] Time step 0 represents the beginning of time step 1 (i.e., the present).
[2] Time step 7 represents the period beyond the planning horizon (contains all pipes not slated for replacement within the planning period.
[3] Discounted cost of breaks before pipe replacement
[4] Discounted cost of breaks after pipe replacement

Violation of this constraint carries a penalty that reduces the probability of the violator scheme of producing offspring. Figure 2 illustrates an example of a scheduling scheme and table 2 summarises the characteristics of the optimal scheduling scheme in the long-term planning phase. Note that the present value of the residual value of this scheme was $3,418,872 and therefore the total discounted cost of this scheme amounted to $8,943,550 (= sum of maintenance and replacement minus residual value).

4.3 Short-term planning

The pipes slated for replacement in time steps 0, 1, 2 of the optimal scheduling scheme are considered as candidates for replacement in the short-term planning phase, i.e., in this example a total of 60 candidates. These candidates are represented by dashed lines in Figure 2. Additionally, scheduled roadwork projects are marked by red triangles with their associated planned year. The short-term planning horizon was taken as 5 years, and it was assumed reasonable to expect roadwork plans for the next 5 years. Economies of scale considerations, as well as savings due to coordination of pipe replacement with roadwork, were considered in the manner described in detail in [11]. However, in addition to the method described in [11], the process described here also introduced the hydraulic constraint (i.e., conformance to minimum nodal pressure of 20 m).

As Table 1 indicates, it was anticipated that coordination with roadwork might save 20% of pipe installation cost and quantity discount of up to 10% (depending on quantity) is also available. Further, mobilisation cost for a set of contiguous pipes was assumed to be $2,000 (therefore additional savings would result if replaced pipes were not scattered but rather concentrated in a few contiguous clusters.

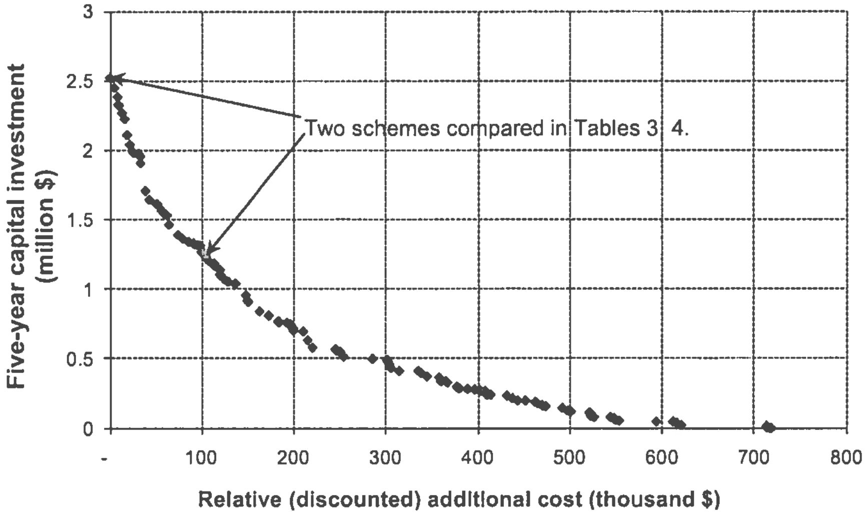

Figure 4. Optimal solutions for short-term planning phase, for various investment levels.

Table 3. Characteristics of the high-investment scheme (costs rounded to $000).

	Year					
	1	2	3	4	5	**Total**
Total length to replace (m)	2,005	1,505	0	1,829	1,475	6,814
# of pipes to replace	19	11	0	11	8	49
# of alignments with roadwork	1	1	0	0	0	2
Savings due to roadwork alignment ($)	18,000	10,000	0	0	0	28,000
Savings due to contiguities ($)	10,000	0	0	0	2,000	12,000
Saving due to quantity discount ($)	86,000	54,000	0	76,000	61,000	278,000
Total savings ($)	114,000	64,000	0	76,000	63,000	318,000
Expected # breaks avoided	20	8	5	5	3	41
Total investment in replacement ($)	749,000	520,000	0	687,000	564,000	2,520,000

Table 4. Characteristics of medium investment scheme (costs rounded to $000).

	Year t					
	1	2	3	4	5	**Total**
Total length to replace (m)	2956	0	401	0	0	3,358
# of pipes to replace	27	0	2	0	0	29
# of alignments with roadwork	0	0	0	0	0	0
Savings due to roadwork alignment ($)	0	0	0	0	0	0
Savings due to contiguities ($)	14,000	0	0	0	0	14,000
Saving due to quantity discount ($)	122,000	0	0	0	0	122,000
Total savings ($)	136,000					136,000
Expected # breaks avoided	20	5	5	4	4	38
Total investment in replacement ($)	1,085,000	0	172,000	0	0	1,257,000

Optimal short-term scheduling scheme was searched using the MOGA tool [13]. It should be noted that the reason why MOGA is used (rather than single objective GA) is that in the short term planning we consider two objectives, namely minimising total discounted costs and minimising capital investment level.

The MOGA produces a Pareto set of non-inferior solutions for pairs of investment levels and total discounted costs, as is illustrated in Figure 4. Tables 3 and 4 provide details for comparison of two sample optimal renewal scheme that corresponds to capital investment levels of $2,520,000 and $1,257,000 respectively. Higher capital budget calls for the replacement of 49 (of 60 candidates) in five years, compared to 29 pipes with medium capital budget, but in both cases a large number of pipes are to be replaced in year 1, indicating a relatively deteriorated network. The high capital investment allows to benefit from $318,000 of savings due to economies of scale and coordination with roadwork, compared to only $136,000 of savings with the medium capital investment. Additionally, the higher capital investment helped to increase the expected number of breaks avoided by a modest 3 breaks (from 38 to 41 breaks). The same framework can be used to formulate strategies with various scenarios of capital budget constraints.

5. CONCLUDING COMMENTS

The optimal scheduling of the renewal of water distribution mains is a highly dimensional problem, for which a comprehensive solution can be found using a two phase approach. The long-term phases produce a list of candidates to be considered for renewal in the short-term. Scheduling in the short-term can consider issues like economies of scale as well as coordination with adjacent infrastructure. In both the long and the short term phases both the structural deterioration (i.e., increase in breakage rate) of the pipes as well as their hydraulic capacity deterioration are considered simultaneously.

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