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SIMULTANEOUS OPTIMIZATION OF PIPE AND PAVEMENT RENEWAL SCHEDULING

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ABSTRACT

Most urban distribution water mains are located under paved streets or roads. Despite an obvious interdependence between pipe and pavement deterioration, this interdependence has not yet been considered in framework that would optimize both simultaneously, which is the issue addressed in this paper. The deterioration processes of both pipe and pavement are considered to be deterministic and some assumptions are made about the interactions between pipe breakage frequency and pavement condition. Total life cycle costs of both pipe and pavement are computed as the discounted costs of an infinite series of perpetual renewal cycles. Genetic Algorithm (GA) is used to find the (near) least cost strategy for scheduling multiple pipes and pavements in a network.

INTRODUCTION

A large number of models exist in the literature for prioritizing water mains for renewal, through optimal scheduling and optimizing the selection of renewal alternatives. Many of these models use cost-minimization as an objective, while others propose a multi-objective decision support approach. Some of these models are used as a basis for decision support software packages.

Most urban distribution water mains are located under paved streets or roads. In a recent workshop held in Denver for a Water Research Foundation project, practitioners from several water utilities stated that whether or not a street has been recently paved, or alternatively is planned to be paved in the near future, has a significant impact on pipe replacement scheduling.

When a pipe breaks, the repair most often results in a pavement patch and pipe replacement will lead to an extensive patched area unless it is coordinated with a street re-paving action. These patches degrade the pavement and shorten its service life. Despite the fact that there is an obvious interdependence between pipe and pavement deterioration, there is little documented evidence of attempts to explicitly consider this interdependence in a framework that would optimize both simultaneously. This paper proposes an approach to simultaneously optimize the rehabilitation scheduling of pipe and pavement.

In the approach proposed in this paper to simultaneously optimize the rehabilitation scheduling of pipe and pavement, the deterioration processes of both are considered to be deterministic and some assumptions are made about the interactions between pipe breakage frequency and pavement condition. As the resulting equations are neither linear nor smooth, they do not lend themselves to analytical solution. Consequently the problem is discretised and solved using genetic algorithm.

PAVEMENT RENEWAL AND COST

For the representation of pavement deterioration and renewal we largely rely (including notation) on the work by Li and Madanat (2002), who improved on earlier work by Tsunokawa and Schofer (1994). Accordingly, pavement condition (or roughness) as a function of time is denoted $S(t)$ and is expressed in units of QI (Quarter car Index – counts per km).

$$S(t) = S_0 e^{ft} \quad (1)$$

where S_0 is some baseline value of pavement condition and f represents the rate of deterioration. Two cost components are associated with pavement, namely user cost and agency cost. User cost, C [\$/unit length] at time t , is a function of pavement condition at t and is defined by (c_{1-2} are constants)

$$C[S(t)] = c_1 S(t) + c_2 \quad (2)$$

An improvement function that defines the improvement from pavement condition S_2 , (immediately prior to rehabilitation) to condition S_1 (immediately after) is given as

$$S_2 - S_1 = g_1 W^{0.5} + g_2 S_2 + g_3 \quad (3)$$

where W [mm] is the thickness of the repavement layer (w is also called resurfacing intensity) and g_{1-3} are constants obtained from World Bank data (Watanatada et al 1988). Agency cost M [\$/unit length] is given by (m_{1-2} are constants):

$$M = m_1 W + m_2 \quad (4)$$

The resurfacing optimization problem addressed by Li and Madanat (2002) comprised two decision variables, namely timing and intensity of repavement, however, one of their main conclusions was that "...a good strategy is to rehabilitate the pavement to the best achievable level, even if this is not scheduled at the optimal time". They noted that this conclusion was consistent with other researchers' findings. Consequently, in the approach proposed here we assume for simplicity that the agency will always resurface to the best achievable level S_1 , which reduces the problem to a single decision variable (timing).

Consider a full renewal cycle, in which the pavement starts at condition S_1 and then allowed to deteriorate to S_2 over a time period t , upon which it is repaved back to condition S_1 . The discounted total cost Cs of this single renewal cycle, comprising user and agency costs, is given by (e^{-rt} is the continuous form of discounting at a discount rate of r)

$$Cs = \int_0^t [C_1 S_1 e^{fu} + C_2] e^{-ru} du + M e^{-rt}$$

$$M = m_1 \left[\frac{S_2 - S_1 - g_2 S_2 - g_3}{g_1} \right]^2 + m_2 \quad (5)$$

$$S_2 = S_1 e^{ft}$$

Consider further a perpetual set of consecutive renewal cycles from time zero to infinity. For simplicity it is assumed that these renewal cycles are identical, ignoring possible future changes such as new pavement materials, technologies, costs, etc. It can be shown that the total cost C_{inf} , discounted to time zero, of this infinite series is given by

$$C_{inf} = \frac{Cs}{1 - e^{-rt}} \quad (6)$$

The value of t (cycle duration) that minimizes C_{inf} is denoted by t_v^{**} , and can be computed numerically (there is no close-form solution). Consider now the general case in which pavement current condition is S_v and S_I is the best achievable level of resurfacing ($S_v > S_I$). The total discounted life-cycle cost of the pavement from present to infinity C_{life} is given by

$$C_{life} = \int_0^t [C_1 S_v e^{fu} + C_2] e^{-ru} du + M e^{-rt} + C_{inf}(t_v^{**}) e^{-rt} \quad (7)$$

$$M = m_1 \left[\frac{S'_2 - S_1 - g_2 S'_2 - g_3}{g_1} \right]^2 + m_2$$

$$S'_2 = S_v e^{ft}$$

The optimal time t_v^* for the next repavement is the value of t that minimizes C_{life} and can be computed in close-form (for typical values of the various parameters):

$$t_v^* = \frac{1}{f} \ln \left[\frac{-b + (b^2 - 4ac)^{0.5}}{2a} \right] \quad (8)$$

$$a = S_v^2 (2f - r) (1 - 2g_2 + g_2^2)$$

$$b = 2S_v (f - r) \left[\frac{g_1^2 C_1}{2m_1 (f - r)} - S_1 - g_3 + S_1 g_2 + g_2 g_3 \right]$$

$$c = \frac{C_2 g_1^2}{m_1} - 2g_3 S_1 r - S_1^2 r - g_3^2 r - \frac{g_1^2 m_2 r}{m_1} - \frac{g_1^2 r}{m_1} C_{inf}(t^{**})$$

It is easy to show that repavement at optimal timing t_v^* will always occur when pavement reaches condition S_2 , which does not depend on S_v (i.e., given S_I and a set of parameters $r, f, g_{1-3}, m_{1-2}, C_{1-2}$, optimal repavement will always occur at the same condition S_2 , regardless of the current condition of the pavement).

PIPE RENEWAL AND COST

Pipe life-cycle renewal cost analysis is done in a manner similar to the one articulated for pavement. Denote pipe failure intensity $\lambda(t)$ [# / unit time / length] as a function of time (or pipe age). The total cost of a single life cycle from new (excluding first installation) to first replacement (inclusive) is expressed by

$$C_{sp} = \int_0^t c_f \lambda(u) e^{-ru} du + C_r e^{-rt} \quad (9)$$

where t is time of replacement, r = social discount rate, C_r is cost of replacement; and C_f is cost of failure (could include repair, water loss, indirect cost, social cost, etc.). Consider further a perpetual set of consecutive renewal cycles from time zero to infinity. Under the assumption of identical

behavior and costs through all cycles, it can be shown (similar to the pavement case) that the total cost C_{inf_p} , discounted to time zero, of this infinite series is given by

$$C_{inf_p} = \frac{Cs}{1 - e^{-rt}} \quad (10)$$

The value of t (cycle duration) that minimizes C_{inf_p} is denoted by t_p^{**} , and can be computed numerically (no close-form solution) for various forms of deterioration functions $d[\lambda(t)]/dt$. Consider now the general case in which pipe current failure intensity is $\lambda'(u)$. The total discounted life-cycle cost of the pipe from present (time zero) to infinity C_{life_p} is given by

$$Cs_p = \int_0^t c_f \lambda'(u) e^{-ru} du + C_r e^{-rt} + C_{inf_p} e^{-rt} \quad (11)$$

The optimal time t_p^* for the next replacement is the value of t that minimizes C_{life_p} and can be computed in close-form for exponential deterioration (i.e. $d[\lambda(t)]/dt = ae^{bt}$: where a and b are constants). For example, if failure intensity at present is a and increasing at a rate of e^{bt} then (similar to Kleiner et al., 1998a).

$$t_p^* = \frac{1}{b} \ln \left[r \frac{C_r + C_{inf_p}(t_p^{**})}{C_b a} \right] \quad (12)$$

INTERACTIONS BETWEEN PIPE AND PAVEMENT

There are no hard data upon which pipe-pavement life-cycle interaction can be established with any rigor. The following assumptions are therefore made for this analysis.

- Pipe replacement accelerates pavement deterioration rate from $S_0 e^{f_1 t}$ to $S_0 e^{f_2 t}$ ($f_2 > f_1$).
- Pipe repair impact on pavement deterioration is already accounted for in the normal deterioration rate. Similarly, pavement condition and deterioration impact on the pipe is assumed to already be manifested in the pipe normal deterioration rate.
- If pipe replacement is done simultaneously with road repavement then the combined cost of renewal will be reduced by m_3 [\$/km] compared to the cost of renewal at different times.
- Open trench replacement of pipe soon after repavement carries a social cost (public disapproval) of $B = m_4(t_s - t_e + 1)/t_s$, where t_s is a threshold value and t_e is the time elapsed from the last repavement to the following pipe replacement ($B=0$ for $t_r > t_s$).
- Repavement (if done carefully) does not affect pipe condition or deterioration rate in any way.

Consider a planning period starting at t_0 where, t_v^* (calculated from Equation [8]) is the preferred repavement timing, t_p^* (calculated from Equation [12]) is the preferred timing for pipe replacement and t_s is a threshold of, say, 4 years. Three scenarios can be observed:

- Pipe is replaced before repavement ($t_p^* < t_v^*$).* Pavement deterioration is computed based on some deterioration rate f_1 (prior to pipe replacement). If the pipe is subsequently replaced before the end of the planning period then after pipe replacement pavement deterioration rate increases to f_2 and consequently t_v^* is no longer at its original values but rather sooner. Subsequent repavement (which may fall within or past the planning period) will take place sooner.
- Pipe is replaced after repavement ($t_p^* > t_v^*$).* Here too, pavement deterioration rate increases from f_1 prior to pipe replacement to f_2 after pipe replacement. In addition, if the pipe is replaced two years after repavement then a cost of $B = m_4(4-2+1)/4 = 0.75m_2$ is imposed.

- c. *Pipe replacement coincides with repavement* ($t_p^* = t_v^*$). Cost is reduced by m_3 and pavement deterioration rate remains unchanged at f_1 .

As was articulated earlier, costs of both pipe and pavement are computed as the present value of all future cost streams. However in general, renewal cycles of pipe and pavement are not harmonious and therefore any attempt to account for their interactions beyond a planning horizon of reasonable length will result in computationally near-impossible dimensionality. Moreover, the practicality of such refined schedule planning is typically limited to short to mid-term planning, i.e., 5 to 20 years range. In the proposed approach, discounted infinite stream of costs are considered, however, pipe-pavement interactions are only accounted for during the planning period (and in one case, when pipe replacement is later than repavement interaction is considered until the next repavement, which can occur beyond the planning horizon). It should be noted that this approach obviates the need to consider residual values of pipe and pavement at the end of the planning period. However, in future research, when hydraulic capacity of the water distribution is considered as a constraint, residual hydraulic capacity at the end of the planning period will have to be considered (Kleiner et al., 1998b).

EXAMPLE

The proposed approach is demonstrated with an example comprising a synthetic inventory of 20 coupled road-pipe sets (Table 1), where each couple is assumed to completely overlap lengthwise. As hydraulics and economies of scale are not considered here, the network topology is irrelevant.

Pipe costs and breakage rates were selected so as to make them realistically considered for replacement in the next 0-30 years. This corresponds to the assertion in the previous section that this type of refined scheduling would be undertaken only for short to mid-term planning. Breakage rate increase was assumed exponential with constant $a = 0.2$ breaks/km/year (Equation 12) shared by all existing pipes, and break rate increase rate b provided for each existing pipe in Table 1. Pipe replacement costs were taken as \$600, \$500 and \$400 per meter for 10", 8" and 6" pipes respectively. Costs of breakage (repair, water loss, damages, etc.) were taken as \$10,000, \$8,000 and \$6,000 per event. Parameters a and b (initial breakage rate and break rate increase) for replacement (new pipes) were taken as 0.1 and 0.02 respectively, under the assumption that the new pipes will enjoy better performance than the existing pipes..

Pavement performance parameters and costs (Table 3) were borrowed from Li and Madanat (2002), who in turn relied on the parameters of Tsunokawa and Schofer (1994). Three classes of roads are used here. Class A, was assigned parameters identical to those of Li and Madanat (2002), corresponding to a rather major road with traffic volume of 4 million vehicles per year. Class B parameters were scaled down to approximate a secondary road of about 2 million vehicles per year and Class C corresponds to about 1.33 million vehicles per year. The best achievable road condition was assumed to be $S_I = 30$ QI for all road classes. Discount rate for all costs was taken as $r = 0.03$, which corresponds to a social discount rate (as opposed to financial discount rate) appropriate for these type of public projects.

Pipe pavement interaction parameters were assumed the following: discount for simultaneous pipe replacement and repavement was taken as m_3 equals to 20% of pipe replacement cost. Penalty $B = m_4(t_s - t_e + 1)/t_s$, was considered with $m_4 = \$50,000$ and threshold $t_s = 4$ years. Pavement deterioration following pipe replacement $f_2 = 0.07$ (see also Table 2).

As benchmark for comparison, total cost was computed for each pipe and each pavement based on their respective, de-coupled optimal renewal times (i.e., t_v^* and t_p^*).

Table 1. Pipe and road characteristics

No.	Length (km)	Pipe			Road	
		Diam (in.)	age	Brk. rate increase	Class	Condition S_v
1	0.5	8	81	0.026	B	40
2	0.8	6	85	0.025	C	43
3	0.4	6	93	0.023	C	55
4	1.2	8	74	0.024	C	49
5	0.9	10	67	0.030	A	45
6	0.9	10	65	0.031	A	52
7	0.3	6	44	0.033	C	47
8	0.5	6	62	0.028	C	47
9	0.6	8	61	0.030	C	55
10	0.7	6	79	0.031	C	49
11	0.7	8	86	0.030	B	43
12	0.6	8	80	0.026	B	47
13	0.4	6	78	0.029	B	45
14	1.1	6	86	0.027	C	49
15	1.3	6	51	0.033	C	55
16	0.8	10	94	0.024	A	57
17	0.5	6	102	0.022	C	52
18	0.8	6	49	0.034	B	45
19	0.4	8	68	0.029	B	47
20	0.3	8	86	0.026	C	49

Table 2. Pavement characteristics

Parameter	Symbol	Class A	Class B	Class C
Deterioration rate	f_1	0.05	0.05	0.05
	f_2	0.07	0.07	0.07
User Cost [\$/km]	C_1	1,000	500	333
	C_2	0	0	0
Repavement cost [\$/km]	m_1	3,000	1,600	1,200
	m_2	150,000	85,000	60,000
Improvement parameters	g_1	5.0	5.0	5.0
	g_2	.78	.78	.78
	g_3	-66.0	-66.0	-66.0

Subsequently, the coupled set was run through a GA optimizer (MatlabTM). Results, presented in Table 3, reflect a savings of almost \$1.2M (5%) compared to the benchmark cost. Further, this rather trivial example confirms an intuitive notion that for a given road-pipe couple, whenever their respective t_v^* and t_p^* are close enough it is cost-effective to schedule their renewal for the same year, thus enjoying a discount on pipe installation, avoiding pipe replacement soon after repavement (social cost penalty) and reducing accelerated road deterioration due to pipe works. However, even in this simple example it is not immediately apparent what year should be selected as the year in which pipe and road would be simultaneously renewed.

It appears that the cost curves with respect to time of both repavement (equation [8]) and pipe replacement (equation [12]) are rather flat in the vicinity of t_v^* and t_p^* respectively. Therefore, the increase in cost due to shifting renewal away from of t_v^* or t_p^* is typically not as high as the potential benefit of renewal coordination. However, the fact that pipe renewal is often shifted farther than repavement (e.g., couples number 4, 7, 9, etc.) suggest that shifting pipe renewal is cheaper than shifting repavement.

Table 3. Results: renewal schedule and costs.

No.	Benchmark (t^*) renewal year		Optimised renewal year	
	Pavement	Pipe	Pavement	Pipe
1	12	10	13	13
2	11	12	9	9
3	6	12	6	6
4	8	25	9	9
5	9	6	6	6
6	6	10	9	9
7	9	29	10	10
8	9	25	10	10
9	6	13	5	5
10	8	1	8	8
11	11	1	14	14
12	9	11	7	7
13	10	6	4	4
14	8	4	7	7
15	6	22	10	10
16	4	3	6	6
17	7	8	6	6
18	10	22	11	11
19	9	14	10	10
20	8	5	4	4
Cost (\$000)	18,443	6,856	17,118	7,016
Total (\$000)	25,299		24,134	

CONCLUDING COMMENTS

The proposed approach to harmonise pipe and pavement renewal planning and optimization is simple and intuitive in its current form. In fact, it should be noted that the GA reached a sub-optimal solution, in which couples number 3, 8 and 18 were scheduled to be renewed in years different than in Table 3. Intuition and a bit of trial and error helped to find a modest improvement (about \$80K) with the renewal years reflected in Table 3.

To make the approach more realistic other considerations need to be incorporated, such as water network hydraulic constraints, economies of scale, optimization under budget constraints and a less restrictive coupling of pipe and road. The incorporation of these considerations will produce solutions that are no longer trivial and intuitive, as the dimensionality of such a problem can be vast.

As this is a first attempt at solving this coupled problem, it is hoped that this first attempt will stimulate more research, leading to improvements and refinement. Moreover, in the current municipal asset management environment different classes of assets, such as pipes and pavements, are largely managed in isolation (silos), leading to sub-optimal results. The existence of a theoretical framework to consider integrated management of multi-class assets may lead to changes in practice with substantial benefits.

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