Optimal Scheduling of Pipe Replacement, Including Opportunity, Social and Environmental Costs

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Summary: The renovation period for a pipe is usually calculated by minimizing the sum of the renovation and maintenance costs. In this paper, the optimum period is calculated in a similar way although including additional costs of increasing importance that usually are not taken into account (water lost through leaks, social costs and opportunity costs). Additionally, the influence of the new trenchless technologies is also assessed. Finally, an example allows for the quantification of the influence of the new factors and the interpretation of the opportunity costs.

Keywords: Pipe renovation, cost analysis, trenchless technologies.

1. Introduction

The problem at stake, due to its importance, has been tackled by many researchers. Amongst these, the work by Shamir and Howard (1979) must be highlighted due to its later impact. The authors, admitting an exponential increase in failures with time, obtained the optimum renovation period by calculating the minimum value of the sum of renovation and repair costs. Other authors (Loganathan et al., 2002; H.P. Hong et al., 2006) have followed a similar procedure, even though they admit that the number of failures follows a non-homogeneous Poisson distribution. Kleiner et al. (2001) include other renovation criteria such as the social costs derived from lower standards of service.

Generally speaking, two are the main costs to be taken into account. The renovation costs per meter of main (C_1) and the analogue repair and maintenance costs (C_2). The first ones decrease with time, for the renovation cost is considered constant and the longer the pipe lasts, the smaller the yearly cost in net present value is. The second ones are calculated assuming a time evolution of the failure index and an associated unit cost for repairs.

These analyses ignore some factors which may become significant with time, for instance the cost of the water lost through leaks. In order to correctly assess the influence of these emerging factors in the optimum renovation period, additional costs have to be taken into account. More specifically, the variable costs of water (C_3), social costs (C_4) and the opportunity costs (C_5). Each one of these terms can be broken down in several parts.

For instance, C_3 is the sum of the variable costs of the water lost through leakage (production and environmental costs, C_{31}), and the energy costs resulting from an increased energy used in pressurizing the leaked water as well as roughness in the pipe (and consequently greater energy losses) (C_{32}).

The social cost, C_4, includes two terms. The first one C_{41} -often ignored- relates to the impact created by the repair works (such as traffic interruptions) while the second one C_{42} considers the penalties derived from missing a level of service target (for instance maintaining the standard operating pressure).

Finally, the opportunity cost[1] C_5, is associated to the savings derived from renewing the pipe while performing other utility or road works which are more urgent. As a consequence costs of a certain importance are shared (e.g. machinery, staff, tools, etc.). The savings can even reach the total cost of the installation if other works are in charge of digging and replacing the pavement.

It is quite obvious that the result of the analysis will depend on whether these additional costs are included or not, particularly when the variable cost of water, C_{31}, is high (e.g. desalinated water).

2. Fundamentals

As previously stated, the two main costs considered by Shamir and Howard (1979), C_1 and C_2, have different behavior patterns. These same principles apply to the new costs proposed in this paper. For instance, the social and opportunity costs depend on the installation technology. Table 1 summarizes the notation used and characterizes both the type of cost and the influence of the installation technique on its value.

The pipe renovation cost can be divided into C_{11} and C_{12}. The price of the pipe depends on the pipe material, while the installation costs are related to the

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[1] In this paper, opportunity cost makes reference to the savings obtained when at least part of the installation works are carried out by another company. This concept goes beyond the traditional one designating the cost of investment of the available resources taking advantage of a certain economic opportunity versus other available options (in other words versus the value of a better option not chosen)

installation techniques. The repairs and maintenance costs, C_2, are sensitive to the number of failures and consequently to pipe aging. The cost of water loss through leakage C_{31} and the increase in energy consumption C_{32} are only dependant on the number of bursts, which also increase with time. The social costs C_{41} basically take into account the disruptions caused by the installation, which are dependant on the technology used. On the other hand, C_{42}, which takes into account the cost of providing a lower standard of service, does not depend on it.

Table 1. Characterization of the costs

Cost	***Year of estimation of the cost***	***Sub-cost***	***Does technology have an influence?***	***Cost nature***
C_1 Renovation	t_p t_p	C_{11} Pipe cost C_{12} Pipe installation	No Yes	Investment Investment
C_2 Repairs and maintenance	t_p	C_2	No	Maintenance
C_3 Variable costs related to water	t_p	C_{31} Leakage	No	Maintenance
	t_p	C_{32} Energy losses	No	Maintenance
C_4 Social	t_p	C_{41} Disruptions caused by the works	Yes	Occasional
	t_s	C_{42} Costs related to lower standards of service	No	Maintenance
C_5 Opportunity	t_c	C_5	Yes	Savings in the investment

3. Cost analysis

Determining the optimum renovation period requires the quantification of the time evolution of all costs. In the following analysis, all costs quoted are yearly costs and calculated per meter of mains. This implies that all pipes considered for this analysis need to be homogeneous in age, diameter, material and installation technique used.

Figure 1 shows the time scale for the cost analysis according to Shamir and Howard (1979): t_0 is the first year for which there are available pipe failure data, t_p is the current year, t_r is the renovation year. In addition, t_c represents the year when the installation costs may be reduced due, for instance, to other utility works, and finally t_s is the year in which the service provided falls below the standard level. Once t_r has been calculated, it may happen that either t_c or t_s, or both, may happen later in time. In such case, the initial hypothesis should be re-stated and all values calculated again.

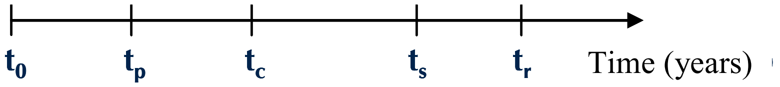


Figure 1. Time scale

3.1. Renovation costs (C_1)

The renovation costs according to Shamir and Howard (1979) are:

$$C_1(t_r) = \frac{C_1}{(1+R)^{tr-tp}}$$

Where C_1 is the pipe renovation cost (€/m) and R the discount rate. If the two components of $C_1(t)$ are considered:

$$C_1(t_r) = C_{11}(t_r) + C_{12}(t_r) = \frac{C_{11}}{(1+R)^{tr-tp}} + \frac{C_{12}}{(1+R)^{tr-tp}}$$

3.2. Maintenance and repair costs (C_2)

The total costs of maintaining and repairing the pipe from the current year until the replacement year is:

$$C_2(t_r) = \sum_{t=tp}^{tr} \frac{C_m(t)}{(1+R)^{t-tp}} = \sum_{t=tp}^{tr} \frac{C_b \cdot N(t_0) \cdot \exp(A \cdot (t-t_0)))}{(1+R)^{t-tp}}$$

Where C_b is the unit cost of repairing a burst. Additionally, t is a generic year between t_p and t_r, and $N(t_0)$ is the number of bursts per length of main in the reference year t_0. Finally A is the annual rate of growth of the number of bursts.

3.3. Variable costs related to water (C_3)

The yearly volume of water lost through leaks is assessed by considering an average unit leakage flow rate q_f, and an average time of duration for the leak, Δt_a. Considering these factors, the volume lost through leaks is:

$$V_f(t) = q_f \cdot N(t_0) \cdot \exp(A \cdot (t-t_0)) \cdot \Delta t_a$$

And consequently the total cost of the leakage volume (C_{31}) from the current year until the replacement year is:

$$C_{31}(t_r) = \sum_{t=tp}^{tr} \left(\frac{q_f \cdot N(t_0) \cdot \exp(A \cdot (t-t_0))}{(1+R)^{t-tp}} \right) \cdot \Delta t_a \cdot C_W$$

Where $C_{31}(t_r)$ is the total accumulated cost associated to the leakage loss volume (until the renovation is undertaken in the year t_r). Then, q_f is the average volume lost per leak (from the current year to the renovation year) and Δt_a is then considered to be half the inspection period for the pipe (during the pipe' life half the interval between sweeps is commonly used). Finally, C_w are the total water related costs in (€/m^3), resulting from the production and the environmental costs.

The cost associated to the energy consumption (C_{32}), is:

$$C_{32}(t_r) = k \cdot \left[\sum_{t=tp}^{tr} \frac{\left(\gamma \cdot \left(q_f(t) \cdot N(t_0) \cdot \exp(A \cdot (t - t_0) \cdot \Delta t_a \right) \cdot \frac{p_s}{\gamma} \right) \cdot C_E \cdot \frac{1}{\eta}}{(1+R)^{t-tp}} \right]$$

Where p_s is the operating average pressure and C_E the cost of the consumed energy in €/Kwh. The efficiency of the pumps is η and k a coefficient defined by Colombo and Karney (2003) quantifying the increase in pressure needed to compensate the existence of leaks (k>1).

3.4. Social costs derived from disruptions caused by the works (C_{41})

C_s represents the social costs derived from the disruption created by the repair works (which is similar to a one time investment, for instance C_1). The net present value is:

$$C_{41}(t_r) = \frac{C_S}{(1+R)^{tr-tp}}$$

This term contains the costs related to traffic disruptions, damage to the pavement and other infrastructures, loss of productivity, business losses, community complaints, increased costs of cleaning services, etc.

4. Other occasional costs

This point covers costs which may, or may not, appear in the latter analysis depending on when and which the solution replacement is finally adopted. When applicable, these costs should be included as indicated here.

4.1. Social costs related to service levels below the standards of service

The social costs due to lower levels of service (for instance low pressure) are to be faced every year between t_s and t_r. A first estimate of these costs would imply a constant penalty, resulting in:

$$C_{42}(t_r) = \sum_{t=ts}^{tr} \frac{C_P}{(1+R)^{t-tp}}$$

Where C_p is the yearly penalty due to the fact that the standards of service are being missed.

4.2. Opportunity costs (C_5)

The opportunity costs can be rendered as a benefit or a negative cost. The opportunity cost may appear in a certain moment, year t_c, and consequently needs to be treated as a step function.

Its maximum range of variation is $0 < C_5 < -C_{12}$, since the term relative to the cost of installing the pipe C_{11} will always be the same.

Traditional techniques of installation would take the value closer to the upper limit, while new trenchless technologies would bring it down to the lower limit.

5. Determination of the optimum renovation period and the minimum cost

The sum of all costs (except C_{42} and C_5 which are not always applicable) is:

$$C_T \equiv C_{11}(t_r) + C_{12}(t_r) + C_2(t_r) + C_{31}(t_r) + C_{32}(t_r) + C_{41}(t_r) \tag{1}$$

The optimum renovation period t_r is calculated by minimizing the total cost function $\frac{\partial C_T}{\partial t_r} = 0$, which substituted in (1) will allow the determination of the minimum cost of the works, $C_T(t_r^*)_{MIN}$. Grouping as (1) the three investment costs C_{11}, C_{12} and C_{41}, with an analogue behavior in time (in € per length unit):

$$C_{11}(t_r) + C_{12}(t_r) + C_{41}(t_r) = \frac{C_{11} + C_{12} + C_S}{(1+R)^{tr-tp}} = \frac{I}{(1+R)^{tr-tp}}$$

It is also convenient to group the annual cumulative costs (C_2, C_{31} and C_{32}):

$$C_2(t_r) + C_{31}(t_r) + C_{32}(t_r) =$$

$$\sum_{t=tp}^{tr} \frac{C_b \cdot N(t_0) \cdot \exp(A \cdot (t - t_0)))}{(1+R)^{t-tp}} + \sum_{t=tp}^{tr} \left(\frac{q_f \cdot N(t_0) \cdot \exp(A \cdot (t-t_0))}{(1+R)^{t-tp}} \right) \cdot \Delta t_a \cdot C_W +$$
$$+ k \cdot \left[\sum_{t=tp}^{tr} \frac{\left(\gamma \cdot \left(q_f(t) \cdot N(t_0) \cdot \exp(A \cdot (t-t_0) \cdot \Delta t_a \right) \cdot \frac{p_s}{\gamma} \right) \cdot C_E \cdot \frac{1}{\eta}}{(1+R)^{t-tp}} \right]$$

Finally obtaining:

$$C_2(t_r) + C_{31}(t_r) + C_{32}(t_r) = M \cdot \sum_{t=tp}^{tr} \frac{\cdot N(t_0) \cdot \exp(A \cdot (t - t_0)))}{(1+R)^{t-tp}}$$

Where:

$$M = C_b + \left(q_f \cdot \Delta t_a \cdot \left(C_W + \frac{k \cdot p_s}{\eta} \cdot C_E \right) \right)$$

With M being an annual "maintenance" cost (also in € per length unit) resulting from pipe aging. In fact includes repair plus water and energy losses.

Taking all these factors into account, the function (1) to be minimized is:

$$Min(C_T(t_r)) \equiv Min\left(\frac{I}{(1+R)^{tr-tp}} + M \sum_{t=tp}^{tr} \frac{N(t_0) \cdot \exp(A \cdot (t - t_0))}{(1+R)^{t-tp}} \right)$$

And the optimum renovation period:

$$t_r^* = t_0 + \frac{1}{A} \ln\left(\frac{I \cdot (\ln(1+R))}{M \cdot N(t_0)} \right) \tag{2}$$

A result which quite resembles the one obtained by Shamir and Howard (1979) but with a wider meaning in the new maintenance and investment parameters M and I. Additionally, the installation technique used influences t_r^* through C_{12} and C_{41}.

6. Example

The numerical example that follows allows you to quantify the influence of the new costs in the problem at stake. The starting data for a polyethylene pipe are:
Cost C_1
Diameter 300 mm, length 1 m, discount rate R = 2%. Costs associated to the renovation (conventional trench and insertion, breaking the pipe with a hydraulic system) as described in Table 2.

Table 2. Price of the polyethylene pipe (€ in the current year)

Diameter (mm)	***C_{11} (€/m)***	***C_{12} (€/m)***	***Total cost (€/m)***
300 (with trench)	70,56	258,57	329,13
300 (trenchless)	70,56	238,44	309,00

Cost C_2

Cost of repairing a single leak = 1400 €

$Nt_0 = 40$ (failures/year/100Km). In the present paper, the current year is the same for which there are available failure data, $t_0 = t_p$.

An annual rate of growth of the number of bursts (1/year). $A = 0.1$.

Cost C_3 (variable cost related to water loss C_3)

$C_w = 0.3$ (€/m^3) Total cost (production and environmental).

$q_f = 15$ (m^3/day) Average volume lost per leak and day.

$\Delta t_a = 182.5$ days. (the network is swept yearly)

$\frac{p_s}{\gamma} = 30$ m.w.c (meters of water column). Average pressure in pipes with leaks.

$C_E = 0.1$ (€/Kwh) Pumping energy costs.

$\gamma = 9810$ N/m^3 Specific weight of water.

$\eta = 0.8$ Efficiency of the equipment.

$K = 1.4$ Energy adjustment coefficient due to leaks.

Cost C_4

$C_{41} = 115$ €/m Social costs, with trench

$C_{41} = 27$ €/m Social costs, no trench

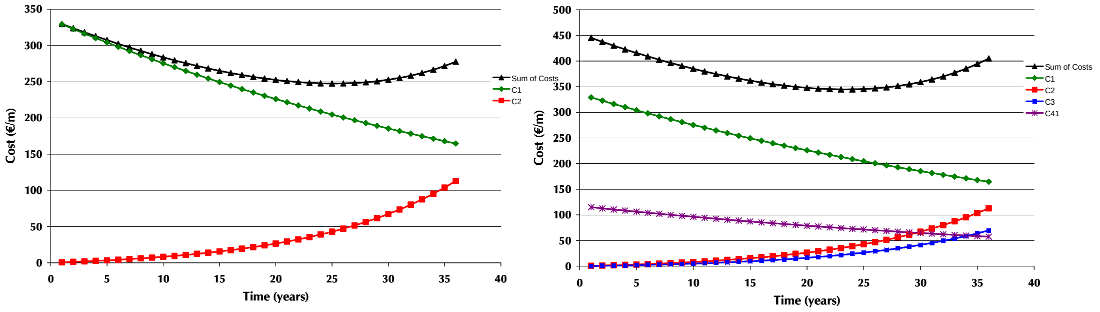
$C_{42} = 2$ €/m Social costs (penalty due to levels below service standards, with $t_s = 10$)

Cost C_5

$C_5 = 15$ (€) Amplitude of the step function of the opportunity cost.

6.1. Influence of the new costs

It was logical to expect that presence of the new costs leads to a shorter renovation period. Figure 2a shows the traditional costs, while Figure 2b shows all considered costs. Finally Figure 3 shows the results. It can be seen that the new costs shift the first curve upwards (higher costs) and towards the y axis (the renovation period is shortened). The optimum renovation period is reduced from 24 to 22 years.



Figures 2 a y 2 b. Time variation (traditional and total costs)

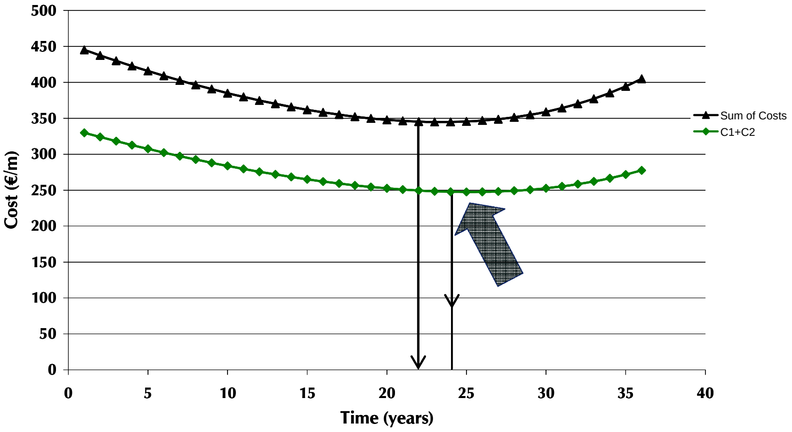


Figure 3. Optimum renovation period (traditional costs vs. Total costs)

6.2. Influence of the installation technology

The installation technology influences the curves, and consequently also affects the optimum renovation period. Figure 4 shows the results for all costs when changing the installation technology. Using a cheaper option reduces the optimum period. As a matter of fact, it is further reduced from 22 to 20 years.

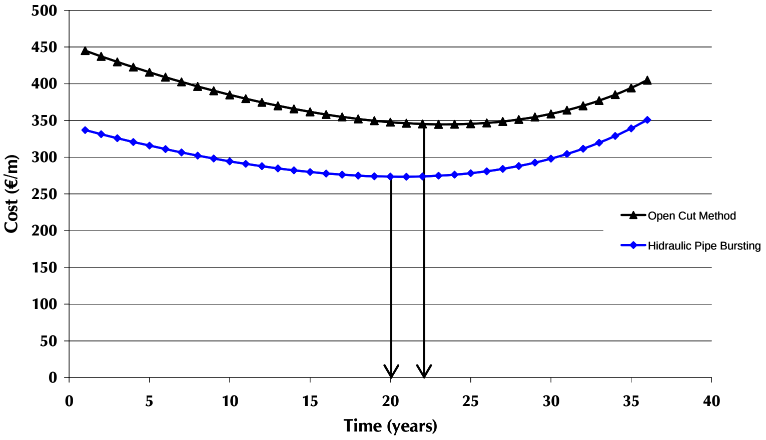


Figure 4. Influence of the installation technology (all costs included)

6.3. Treatment of occasional costs

The social costs generated by missing targets of standards of service or by opportunity costs may or may not become additional costs. When considered, the first one is integrated in the cost structure from year t_s (with $t_s < t_r$) while the second one (negative opportunity cost) only plays a role if the works are carried out in the year t_c. In the first case, missing the standards of service implies that the social costs increase, as reflected by Figure 5. If the pipe is replaced with trench, and taking into account all costs, it is supposed that the standards of services are not met from year

10. The applied penalty further reduces the renovation period, leaving it in t_r = 16 years.

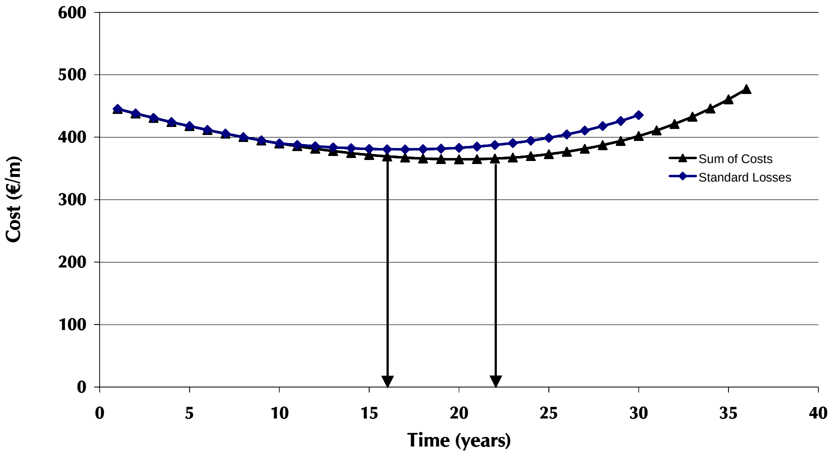


Figure 5. Variation of the total costs when the standards of service are not met

If the opportunity arises of carrying out the works in conjunction with other utilities during the year t_c (always with $t_c < t_r$) the costs curve (Figure 6) is shifted downwards a distance equal to the negative opportunity cost C_5. The comparison between the displaced curves (for the different values of C_5) and the original curve shows the number of years which would be reasonable to anticipate the works. And hence, for savings of 5 €/m, the works should be anticipated from t_r = 16. Higher values (C_5 = 10 ó 15) advice a greater anticipation (t_r = 14 or 13).

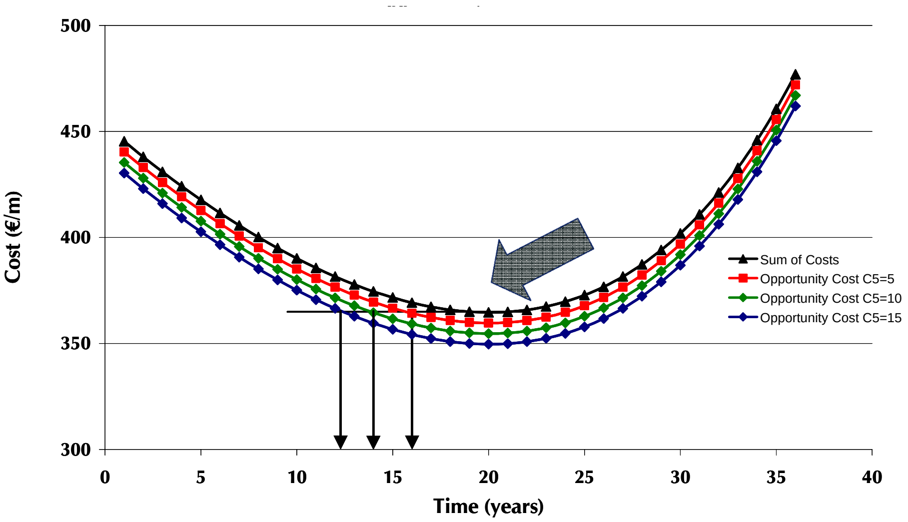


Figure 6. Time shift resulting from opportunity.

7. Conclusions

Qualitatively, the previous analysis bears little surprise. When the new costs rise significantly with time (for instance, water loss through leaks) the optimum renovation period is anticipated, the more with the higher costs. From another perspective, the costs associated to the renovation of the pipe increase the investment, and consequently extend the optimum renovation period. Regarding the technology used, the cheaper the sooner the renovation should be performed. Finally the opportunity costs may anticipate the renovation of the pipe a certain number of years.

Quantitatively, it seems quite obvious that the expressions to assess the new costs must be adapted to each context. The ones included in this paper allow considering with a certain degree of accuracy the influence of these costs which are usually neglected. In any case, and according to previously established objectives, it seems clear that the water loss through leakage must be taken into account, for the production and environmental costs are significant, and they reduce considerably the optimum renovation period.

8. References

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