Effect of Water Costs on the Optimal Renovation Period of Pipes

R. Cobacho*, E. Cabrera*, E. Cabrera Jr. * & M.A. Pardo *

* Institute for Water Technology. Polytechnic University of Valencia. Camino Vera s/n. 46022. Valencia. Spain.

Keywords Cost analysis, cost of water, pipe renovation.

Abstract The determination of the optimum renovation period for pipes seldom includes the cost of the water loss through leaks. This paper presents a complete cost model, which not only includes such costs, but aims to determine the influence of such costs in the whole problem. To this purpose, a case study has been prepared from figures obtained in Spanish utilities. A sensitivity analysis has been performed and a range of the variation of the optimum renovation period has been established for typical values of water production costs and average network pressure. Additionally, secondary influences have been studied.

Introduction

The first reference model with a mention of an optimum renovation period was the one presented by Shamir and Howard (1979). The model, which was based on an exponential increase of failures with time, calculated the optimum renovation period by minimizing a function. The function was the result of adding the repair costs for the life cycle of the pipe and the replacement costs.

In most of the models developed since, problem has been updated by adding or refining the involved costs or by improving the time estimates and their treatment. However, the costs associated to water loss through the leaks have never been included. While this exclusion was probably acceptable in the past, the current context demands to take these costs in to account. For instance, the production costs from desalination plants are quite significant. Additionally, the environmental costs are becoming increasingly important and must be included as an integral part of the optimization problem (as they have already been reflected by new regulations, like the European Water Framework Directive -EU, 2000). In the future, ignoring the influence of these costs may result in solutions which are quite far from the real optimum.

The authors have been working on the topic for a while. Their latest contribution (Cabrera et al., 2007) although considering the costs associated to water loss, had a stronger focus on setting the basic structure of the costs model and evaluating the differences that could exist with previous works. Additionally, the costs associated to the pipe installation technology and the social costs were also considered.

This paper intends to continue such work: starting with the same costs structure for the optimization problem, the influence of the water production costs in the optimization problem will be determined. In order to make such task easier, a new term has been defined: the Maximum Acceptable Leakage Volume (MALV) while taking into account the relationship between the average pressure of the network and the leakage volume.

Revision of the structure and cost calculation

This section describes the costs considered in this work and how they have been evaluated. In order to understand such costs, it is convenient to define some of the time variables beforehand:

- t_p: Current year.
- t_r: Year of pipe replacement.
- t_0: Reference year from which the failures in pipes begin to be accounted for. May be lower or equal to the current year, t_p.

Renovation Costs (C_1)

These are the costs for substituting the old pipe for a new one in Euro per meter of pipe. In current costs, its value diminishes with time, for the renovation cost is considered constant and the longer de pipe lasts, the smaller the yearly cost in net present value is. The model includes its calculation according to the following expression:

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

Where C_1 is the total pipe renovation cost (€/m), $C_1(t_r)$ is the present value of renovation cost expended in the renovation year and R is the discount rate.

Maintenance and repair costs (C_2)

These are the yearly costs needed to maintain the pipe in a good operating state. They are calculated assuming a time evolution of the failure index anda n associated unit cost for repairs according to:

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

Where C_b is the unit cost of reparing a fault. Additionally, t is a generic year between t_p and t_r, and $N(t_0)$ is the number of faults per length of main in the reference year t_0. Finally, A is the annual rate of growth of the number of faults (Shamir and Howard, 1979).

Variable costs related to lost water (C_3)

These costs are, in fact, the sum of the variable actual costs of the water los through leakage (production and environmental costs, C_{31}), and the energy costs resulting from an increased energy use in pressurizing the leaked water, and consequently greater energy losses (C_{32}). Both components will be obtained in turn.

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 present value of the total accumulated cost associated to the leakage loss volume (until the renovation is undertaken in the year t_r), and C_w are the total water related costs in (€/m^3), resulting from the production and the environmental costs.

On the other hand, 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, C_E is the cost of the consumed energy in €/kWh, η is the efficiency of the pumps, and k is a coefficient defined by Colombo and Karney (2003) that quantifies the increase in pressure needed to compensate the existence of leaks (k>1).

In this point, it is necessary to comment on the so called water cost, C_w. Given the objective of the paper, the values assigned to this parameter range between 0.1 €/m^3 and 1.0 €/m^3. This range covers the different possibilities that may be found in current systems, varying from low figures corresponding to accessible and good quality sources, to the higher costs of desalinated water which can be estimated around 0.5 €/m^3; all this without forgetting about the environmental costs suggested to be 0.3 €/m^3 by the Water Framework Directive (EU, 2000).

Social costs (C_4)

Social costs, C_s, are those derived from the disruption created by the repair works (traffic troubles, damage to the pavement and other infrastructures, loss of productivity, business losses, community complaints, etc.), and formally, the are similar to other one-time costs (C_1). So, their net present value C_4 is:

$$C_4(t_r) = \frac{C_S}{(1+R)^{tr-tp}}$$

Though it is in fact a very complex term, but not the aim of this work, social costs will be considered as constant. Further discussion on this matter can yet be found in Cabrera et al. (2007).

Total Costs (C_T)

Once all cost components have been defined and calculated, the total costs included in the problem, planning the pipe renovation in year t_r, may be easily obtained by summing them all:

$$C_T(t_r) \equiv C_1(t_r) + C_2(t_r) + C_{31}(t_r) + C_{32}(t_r) + C_4(t_r)$$

And the optimization of the problem is achieved by minimizing those total costs. According to Cabrera et al. (2007), the optimal renovation period, t_r* (for which total costs become the least possible ones) is calculated like:

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

Where:

$$M = C_b + \left(q_f \cdot \Delta t_a \cdot \left(C_W + \frac{k \cdot p_s}{\eta} \cdot C_E \right) \right) \text{ and } I = C_1 + C_S$$

Although not covered in this paper, the aforementioned optimization can also be studied from different perspectives, obtaining different results. Further details can be found in Pardo (2007).

El Maximum Acceptable Leakage Volume (MALV)

As a side product, the analyses carried out have produced a concept which deserves special consideration due to its significance, the Maximum Acceptable Leakage Volume. This index represents the maximum volume of water lost through leaks per unit of length and time which is produce in the year of renovation of the pipe. It is obtained from the variables already shown:: q_f, $N(t_0)\cdot\exp(A(t-t_0))$ and Δt_a, related by the following equation:

$$IMFT = V_f(t)\left(\frac{m^3}{m \cdot yr} \right) \cdot \left(\frac{1\,yr}{8760\,h} \right) \cdot \left(\frac{1000\,m}{1\,km} \right) = \frac{q_f \cdot N(t_0) \cdot \exp(A \cdot (t - t_0)) \cdot \Delta t_a}{8.76}$$

Example and analysis

The numerical example that follows shows the influence of the mentioned costs in the problem at stake. The starting data, taken from previous works by the authors (ITA, 2006) is referred to a polyethylene pipe.

Cost C_1

- For a 300 mm diameter pipe and considering 1 m length, the renovation costs amount for C1 = 305.3 €/m. For time discounting, the rate will be taken as R = 2%.

Cost C_2

- Cost of repairing a single leak = 1680 €.
- Number of pipe faults for the reference year: $N(t_0)$ = 40 faults/year/100km, taking into account that in this case the reference year is the current year ($t_0 = t_p$).
- Annual rate of growth of the number of faults: A = 0.1 $year^{-1}$.

Cost C_3

- Production and environmental cost of water: Cw = 0.3 €/m^3
- Average volume los per fault and day: q_f = 20 m^3/day.
- Average life for each fault: Δt_a = 160 days.
- Average pressure in faulty pipes: p_s/γ = 25 m.w.c. (metres of water column).
- Pumping energy costs: C_e = 0.1 €/kWh.
- Specific weight of water: γ = 9810 N/m^3.
- Pumping efficiency: η = 0.8.
- Energy adjustment coefficient due to leaks: k = 1.4.

Cost C_4

- Social cost derived from disruptions created by repair works: C_s = 115 €/m.

Influence of water production costs in the optimum renovation period

A first step focuses on the influence of the costs of water over the optimum renovation period. In order to ascertain such influence, the costs have been changed between 0.1 €/m^3 and 0.6 €/m^3. The effect of such increase is visible in the evolution of the costs term, which strictly corresponds to the value of water lost through leaks C_{31} (Figure 1).

Such effect, translated into the duration of the optimum renovation period, produces a significant reduction in its value, given the weight of the variable C_{31}. After calculating the optimum period for each one of the considered costs, the results range from 23.7 years for 0.1 €/m^3 to 18 years for 0.6 €/m^3 (Table 1 and Figure 2).

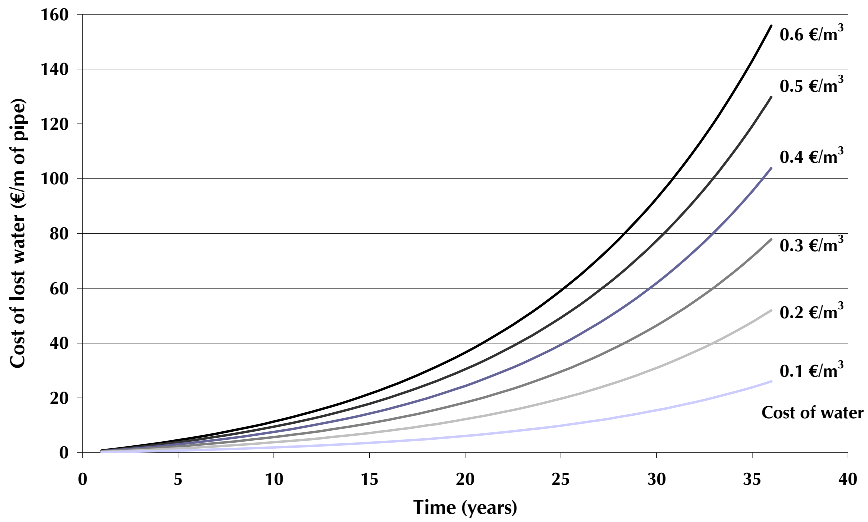

Figure 1. Costs of water lost through leaks (C_{31}), depending on the unit cost C_w

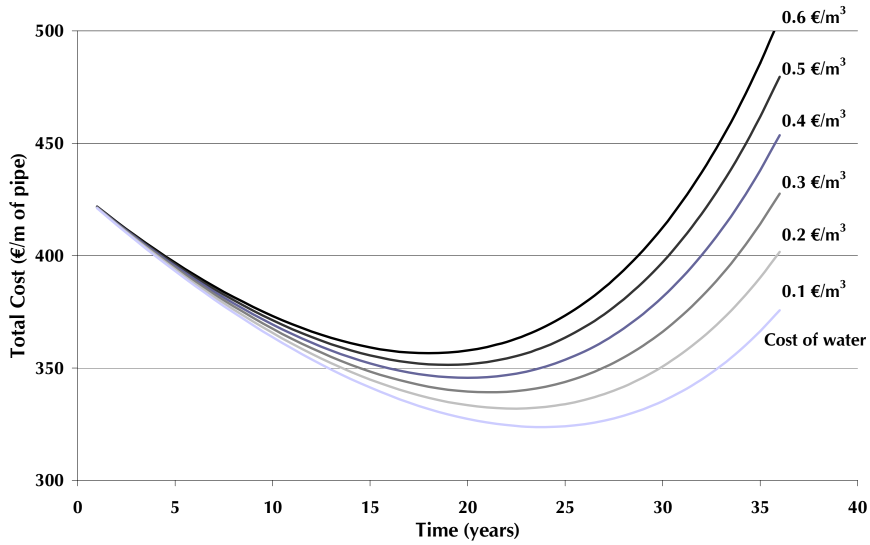

Figure 2. Total costs and renovation period depending on the unit cost C_w

Table 1. Optimum renovation period depending on the cost of water

Cost of water C_w (€/m^3)	Optimum renovation period (years)
0.1	23.7
0.2	22.3
0.3	21
0.4	20
0.5	19
0.6	18

Influence of pipe average pressure in the determination of the optimum renovation period.

In order to illustrate the influence of average pressure in the total costs and the optimum renovation period, it has been changed between 2 bar and 6 bar, maintaining in this case a constant C_w = 0.3 €/m^3 and supposing a proportionality between the average pressure and the leakage flow rate: $q_f' = q_f \cdot (p_s'/p_s)$.

The influence of pressure over costs is, as a matter of fact, double, and it has been evaluated separately (through the water loss –term C_{31}, in Figure 3- and through the energetic costs –term C_{32}, smaller than the previous one, in Figure 4).

From this, the total costs can be easily calculated (Figure 5) and the optimum renovation period corresponding to each case too (Table 2). It can be observed that for a higher average pressure, the optimum renovation period is shorter, for the leakage volume is increased, and so are the costs associated to the leakage volume.

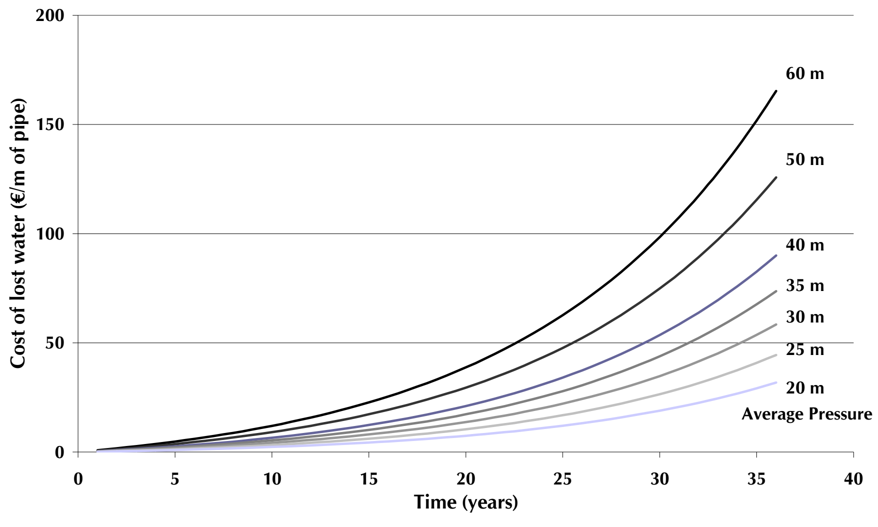

Figure 3. Cost of water lost through leaks (C_{31}) depending on the average pressure (C_w = 0.3 €/m^3)

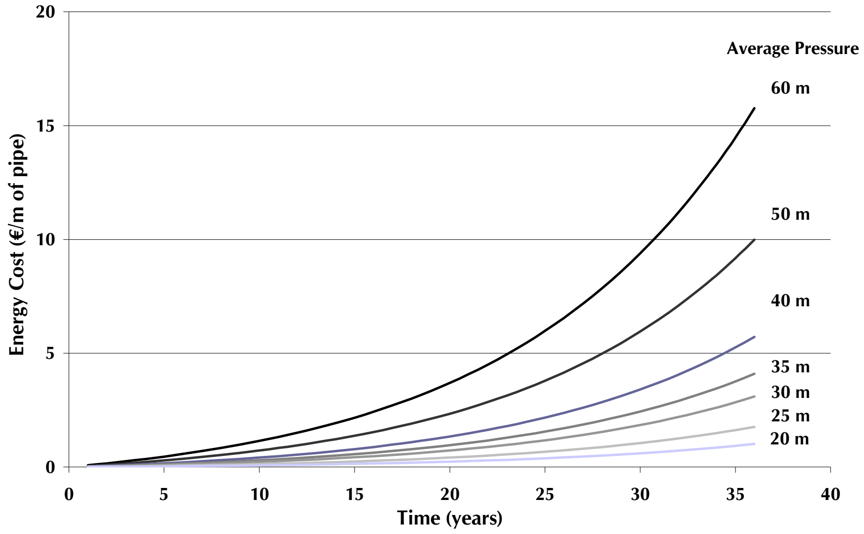

Figure 4. Energy costs (C_{32}), depending on the average pressure (C_w = 0.3 €/m^3)

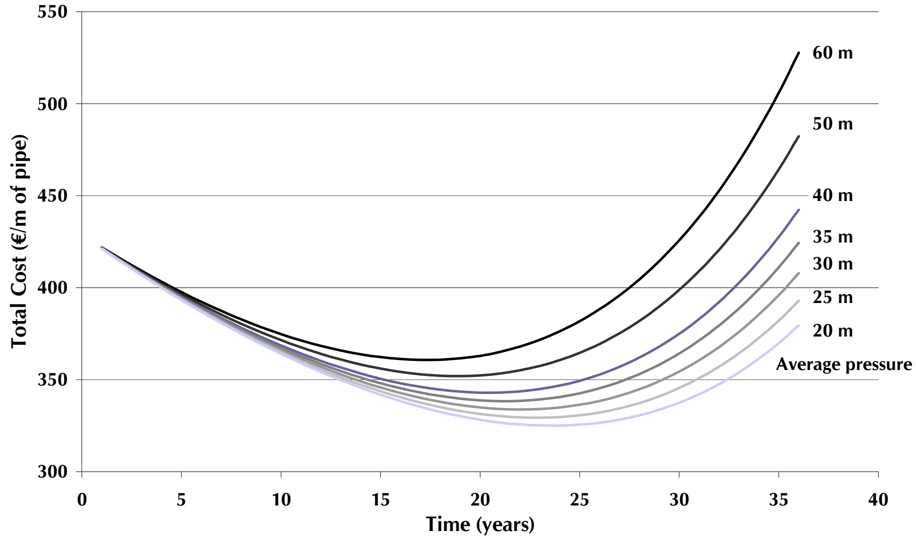

Figure 5. Total costs and renovation period depending on the average pressure (C_w = 0.3 €/m^3)

Table 2. Optimum renovation period values depending on the average pressure (C_w = 0.3 €/m^3)

Avg. pressure (mcw)	Unit leakage flow rate q_f (m^3/day)	Optimum renovation period (years)
20	16	21.84
25	20	21.04
30	24	20.29
35	28	19.59
40	32	18.92
45	40	19.67

Influence of the cost of water on the MALV

From the initial data in the numerical example, this analysis takes into account the effect of the average pressure of the network. This included solving the full problem four times, for average pressure values of 20 mcw (Figure 6), 25 mcw (Figure 7), 30 mcw (Figure 8) and 35 mcw (Figure 9).

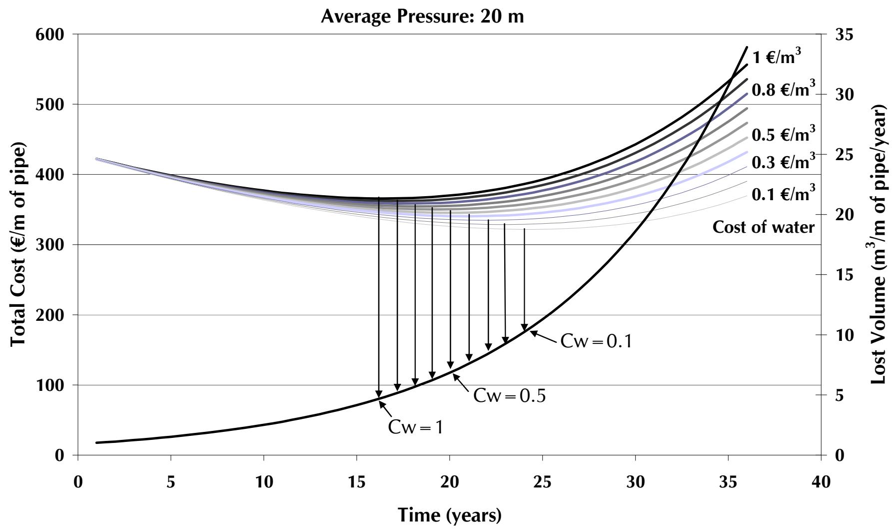

Figure 6. Total cost, leakage volume and optimum period depending on the cost of water (p_s/γ = 20 mcw)

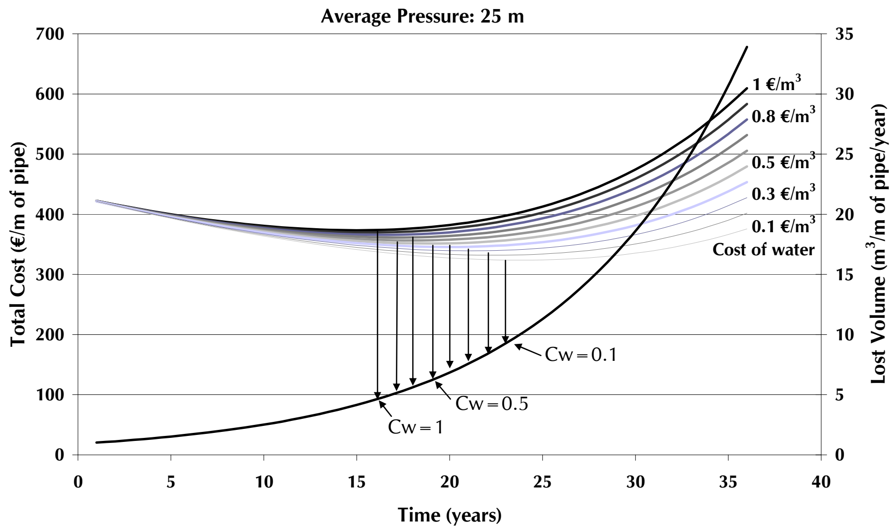

Figure 7. Total cost, leakage volume and optimum period depending on the cost of water (p_s/γ = 25 mcw)

For each case, the values of total costs, optimum renovation period for each value of the cost of water and the leakage volume in the renovation year have been obtained.

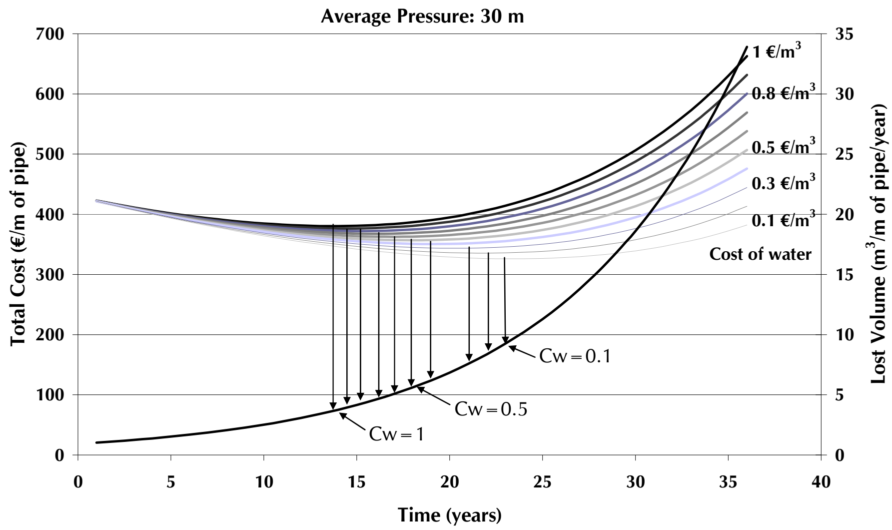

Figure 8. Total cost, leakage volume and optimum period depending on the cost of water (p_s/γ = 30 mcw)

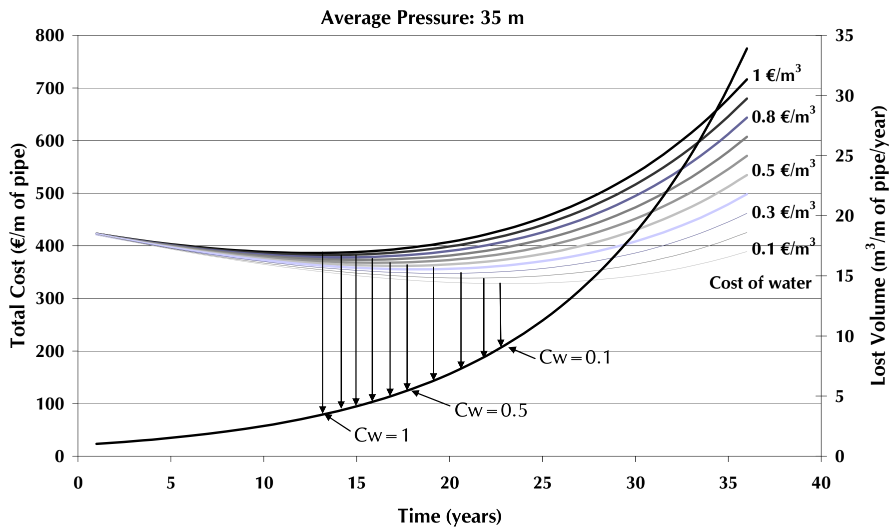

Figure 9. Total cost, leakage volume and optimum period depending on the cost of water (p_s/γ = 35 mcw)

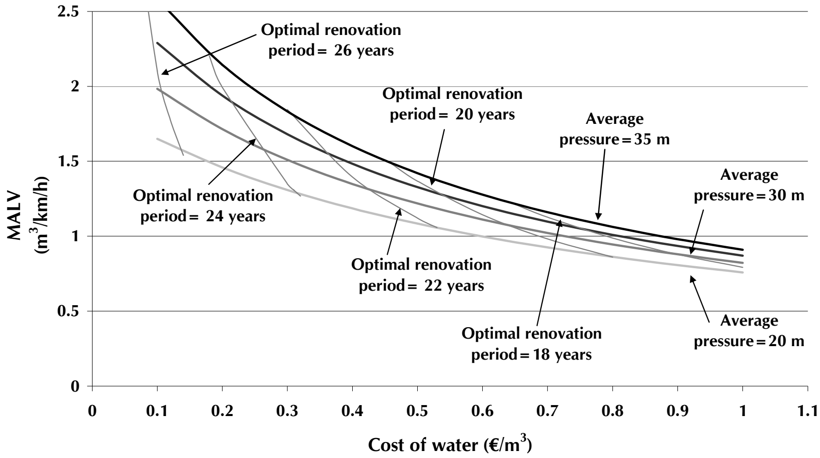

Figure 10. Relationship of MALV, water cost, average pressure and optimum period

From the relevant results in each case, and by combining them with the average pressure of the network, all four parameters have been displayed in a single graph (Figure 10), which clearly shows the expected influence of the cost of water on MALV, and also all the connections between the different factors:

- For a fixed cost of water, the higher the pressure (following a vertical line upwards over the cost) the higher the value of MALV, and the shorter the optimum renovation period. While the first connection is obvious, the second one is explained in the following bullets.
- For a constant average pressure (following the corresponding curve) the relationship between the MALV and the water cost is clear: the higher the water cost, the shorter the renovation period and, as a consequence, the MALV.
- For a reference MALV, taken as constant, there is a direct relationship between the average pressure and the cost of water, and an inverse relationship between any of them and the optimum renovation period.
- The relationship between average pressure and MALV, through the optimum renovation period, is more complex. Since MALV directly depends on the product $N\left(t_r^*\right)\cdot q_f \cdot \Delta t_a$, an increase in the average pressure would increase MALV through a higher unit leakage flow rate. However, such an increase in the leakage flow rate would also produce higher costs of water lost through leaks, pushing the renovation period down, and therefore reducing the $N\left(t_r^*\right)$ term in MALV. Consequently, an increase in average pressure produces two opposed tendencies on MALV components. Although this issue would require further work, it can be stated that in the presented model, the first effect is predominant on the second one, and therefore, although with shorter periods, the MALV is increased.
- Finally, the dependency between average pressure and MALV is increased for lower costs of water (left side of Figure 10), while it practically disappears for high costs (right side of Figure 10).

Influence of a higher failure rate

Another extremely sensitive parameter to the optimum renovation period is the failure rate, A, which represents how well the network is aging from this model's point of view. This term has a direct influence on the estimation of the number of failures that will need to be repaired every year and, indirectly, on the yearly repair and maintenance costs C_2 as shown in Figure 11.

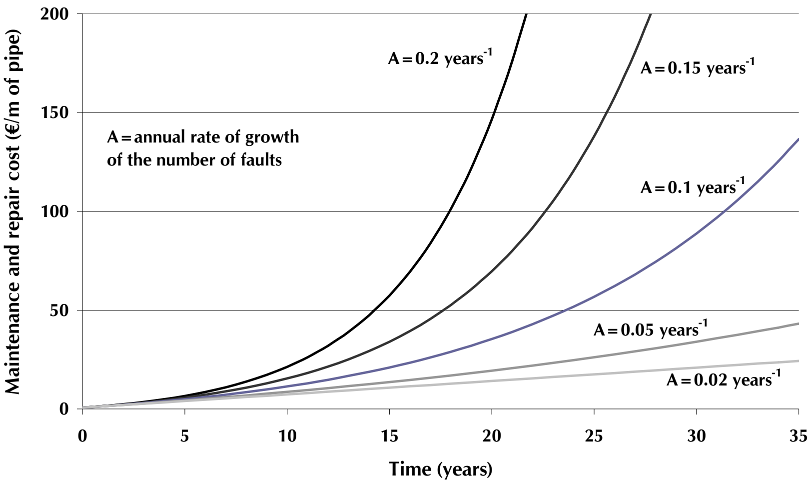

Figure 11. Repair and maintenance costs C2 depending on the optimum period and A

Although it can be guessed from Figure 11, Figure 12 clearly shows the influence of A over the optimum renovation period. As expected, higher values of A yield shorter renovation periods. However, there is an interesting change in slope for values of A close to 0.05 (generic recommendation found in Shamir and Howard, 1979).

Analyzing the influence of the A index over MALV, there is a second focus point, for this influence does not appear in Figure 13). The reason for this is the cancelling effect of the tendencies shown in Figure 11 and Figure 12 when put together to calculate the MALV.

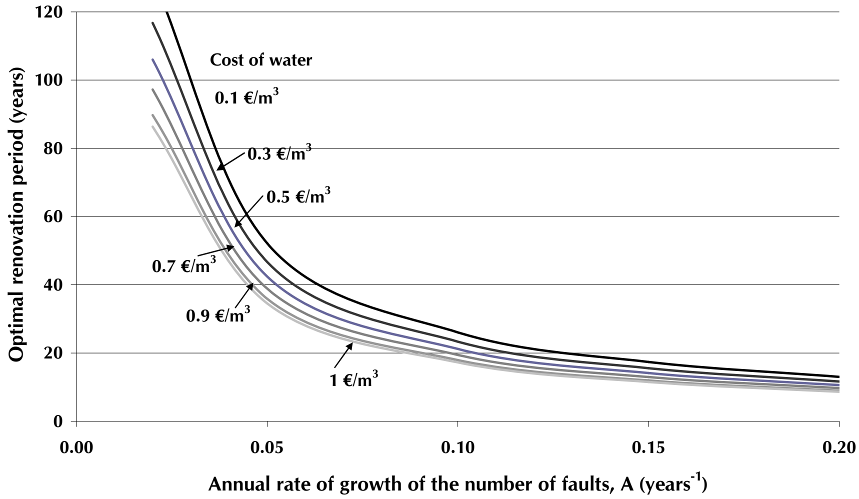

Figure 12. Optimum renovation period depending on A

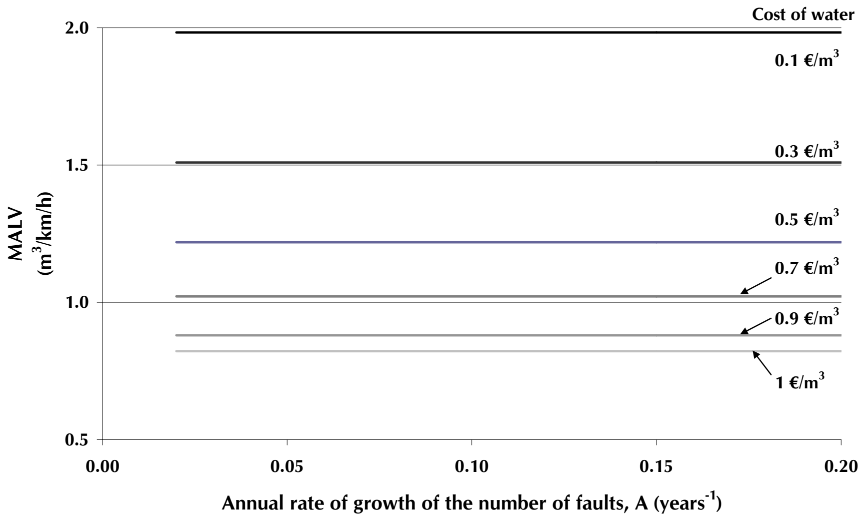

Figure 13. MALV depending on A

Influence of the repair costs

One last factor to be studied is the repair costs. Just like in the previous section, the repair costs will have a direct influence over the C_2 term, and as a consequence results will be parallel to the previous ones. The increase in the repair costs has a direct effect on the reduction of the optimum period (Figure 14), while its influence over MALV (Figure 15) presents the same characteristics as the average pressure of the network.

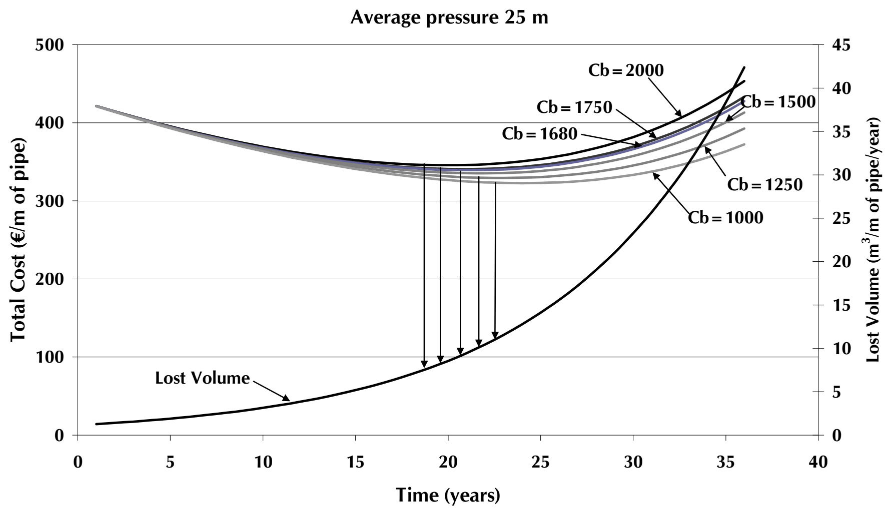

Figure 14. Total cost, leakage volume and optimum period depending on the cost of water (p_s/γ = 25 mcw and C_w = 0.3 €/m^3)

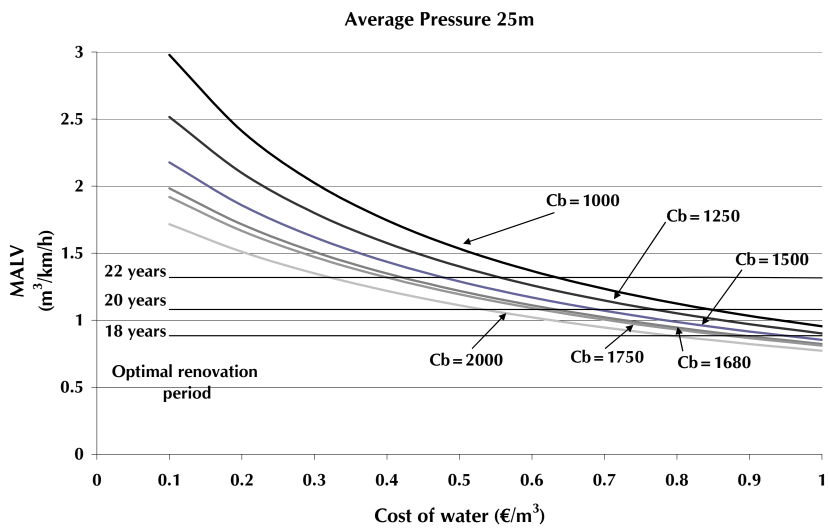

Figure 15. MALV depending on the cost of water and repair costs (p_s/γ = 25 mcw)

Conclusions

Alter presenting a full costs model for the analysis of the optimum renovation period for pipes, this paper has studied the particular influence of water production costs, which is a term not found in previous studies. The model has been applied to a generic case study with average figures referred to a typical Spanish utility. The conclusions are as follows:

- The variation of water costs has a significant influence on the optimum renovation period. The results have not produced any surprises, for if the cost of water increases, the renovation of the pipe needs to take place sooner to minimize costs.
- The Maximum Acceptable Leakage Volume (MALV) has been defined. This is the maximum volume lost through leaks in a linear meter of pipe on the year of renovation. The higher the water costs, the lower the MALV can be, and additionally, the less dependent it becomes from the average leaked flow rate.
- If the MALV is taken as a constant reference, the unit average leaked flow rate would determine the water production cost. Since this scenario would not take place in reality (where the water production costs are related to other circumstances) the figure produced by the model would actually represent a reference of the value of water in the given conditions. The closer that figure is to the real cost of water the greater the consistency of this value will be with the rest of variables in the system.
- Finally, the sensitivity of the optimum renovation period and the MALV have been obtained with respect to other parameters, such as the yearly increase of the failure rate and the renovation costs.

References

Cabrera E., Pardo M.A., Cabrera Jr. E. and Cobacho R. (2007). Optimal scheduling of pipe's replacement, including opportunity, social and environmental costs". *Pipelines 2007.* American Society of Civil Engineers - ASCE. Boston. USA.

Colombo A.F. and Karney B.W. (2002). Energy cost of leaky pipes: Toward comprehensive picture. *Journal of water resources, planning and management.* **128**(6). 441-450.

European Union - EU. (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities.* 22nd of December, 2000.

Instituto Tecnológico del Agua - ITA. (2006). *Control de pérdidas de agua en redes urbanas. Análisis de su incidencia en periodos secos.* Post-graduate course organized by Instituto Tecnológico del agua. Universidad Politécnica de Valencia. Spain.

Pardo M.A. (2007). *Periodo óptimo de renovación de tuberías, incluyendo costes variables del agua, sociales y de oportunidad*. Diploma de Estudios Avanzados. Universidad Politécnica de Valencia.

Shamir U. and Howard C.D.D. (1979). Analytical approach to scheduling pipe replacement. *Journal of American Water Works Association,* **71**(5), 248-258.