J Water SRT — Aqua Vol. 47, No. 6, pp. 275–283, 1998

Exploring rehabilitation needs and strategies for water distribution networks

R. K. Herz, *Chair of Urban Engineering, Dresden University of Technology, Mommsenstr.13, 01062 Dresden, Germany*

ABSTRACT: As water mains become older, failure rates and leakages tend to increase, despite all maintenance efforts, incurring costly repair and rehabilitation measures. Therefore, water utilities striving to prevent their long-lived assets from decline must explore medium to long-term strategies of network rehabilitation and system improvement. Such explorations must start from the existing stock of water mains, differentiated by materials, ages and lifetimes under local conditions, and take into account the frequency of failures, losses by leakage and the extent of rehabilitation work in the past. Utilities will need to develop specific strategies, depending on their rehabilitation philosophy, and pursue them under tight economic and financial restraints. The exploration of network rehabilitation strategies can be facilitated by a model developed at Karlsruhe University [1], and cast into the user-friendly KANEW software in an AWWARF research project [2]. KANEW has been tested and applied in several European and American water utilities [3]. The approach taken, some results and a case study will be presented from Teplice water mains in Northern Bohemia.

INTRODUCTION

The approach

Sooner or later, for a number of reasons, water mains reach the end of their useful lives [3]. Physical deterioration is related to age, and combined with new water supply standards and changes in demand, results in functional deficiencies. Maintenance work will slow down the process of physical deterioration, but repair work will increase over time. Rehabilitation starts when failures and customer complaints can no longer be tolerated. Thus, there is a time period within which installed water mains will require rehabilitation. It is probable that this will occur within a specific time period after installation.

The need for rehabilitation is therefore defined by the total length of water mains reaching the end of their useful lifetime in a given year. This will depend on how many water mains have been installed and rehabilitated in the past and, of course, on how long the specific categories of water mains will last. There can only be an estimated answer to the last question, dependant on local standards and practice. The useful life of a water main may be prolonged at relatively low cost. This depends on the specific costs of repair vs. renewal by different rehabilitation technologies.

Future rehabilitation needs determine future investments, through unit costs of rehabilitation. On the other hand, the rehabilitation of water mains will postpone repair work and leakage losses for some years at least. Thus, the costs and benefits are related to the intensity of rehabilitation. If rehabilitation needs are fulfilled, there will be more benefits than if rehabilitation is postponed and spot repair continues.

Costs depend very much on the rehabilitation rate and on rehabilitation technology. While replacement is more expensive than renovation, the life prolongation of a relined pipe is generally much less than the life of a new one. Thus, relined water mains will create a secondary rehabilitation need after perhaps 30 years and must then be replaced.

The benefits from rehabilitation, relative to ongoing spot repair, are diverse and somewhat intangible. Utilities are mainly concerned about their cost savings from reduced repair work and the leakage of drinking water, and not so much about reducing external costs. However, these so-called social costs [4] are of growing concern to politicians and the public.

Figure 1 illustrates the approach that was taken for exploring rehabilitation needs and strategies in the context of this paper in general, and in the case study of Teplice in Northern Bohemia in particular. It starts from an inventory of water mains, differentiated by the periods of installation for the various types of pipes (Fig. 2). Failure and rehabilitation statistics are analysed in order to estimate the range of lifetimes for the various types of pipe. Survival functions are then defined for the lower and upper lifetime estimate for each type of pipe (Fig. 4), and applied to the cohort-survival model in order to determine the length of pipes reaching the end of their useful life in any year. The extent to which this rehabilitation need is fulfilled is determined by various strategic options. Specific strategies are then evaluated in economic and other terms, and modified until a strategy evolves that best suits the water utility.

THE COHORT SURVIVAL MODEL

The model stems from demography, where cohort survival analysis is widely used to forecast population changes from

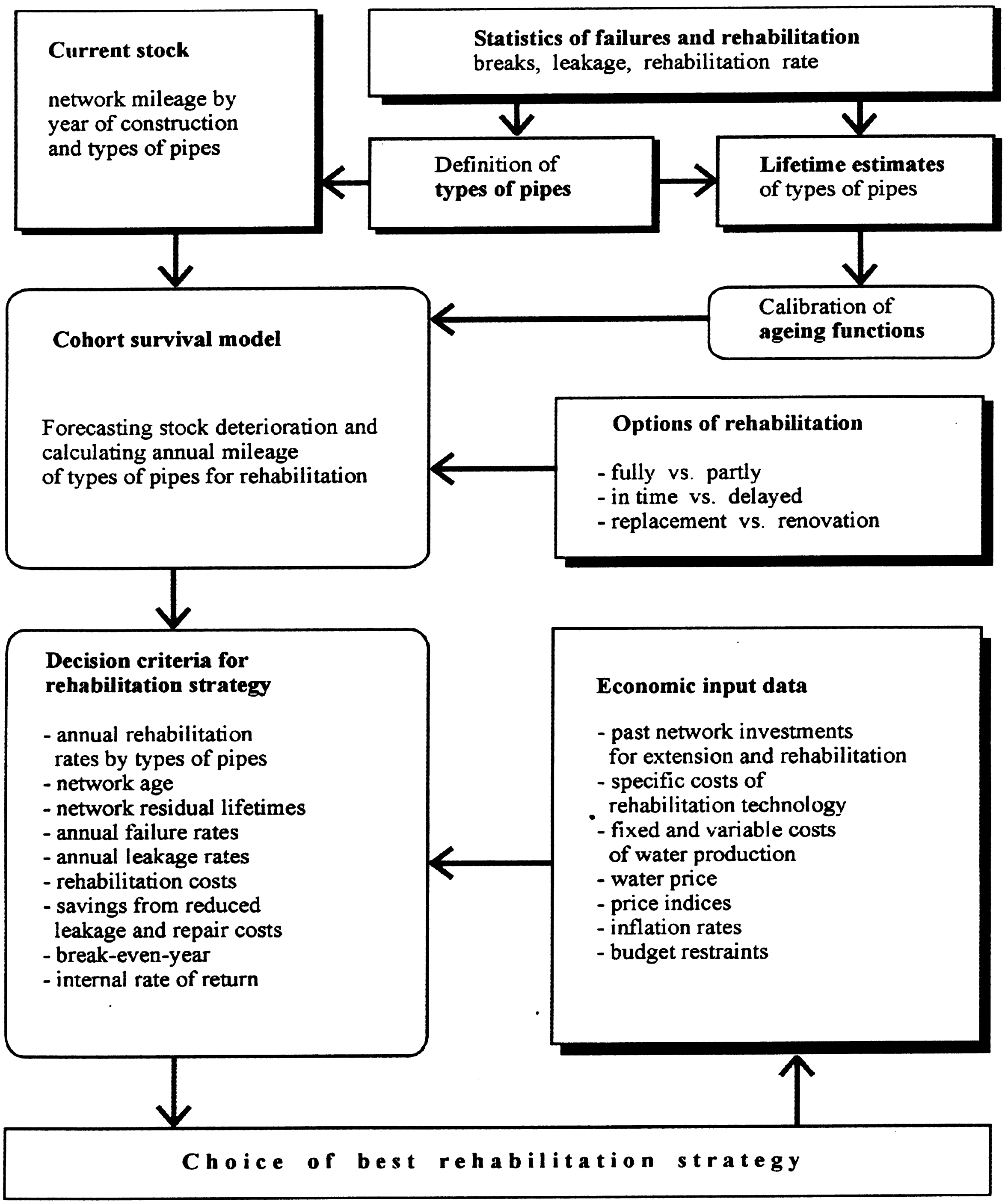

Fig. 1 Framework for exploring water mains rehabilitation needs and strategies.

mortality and fertility statistics [5]. Failure of the infrastructure corresponds to mortality and leads to rehabilitation. This can be expressed in mathematical terms. The mathematics of the model have already been published [1,3,6], so it will be sufficient here to present its basic features.

The types of pipe that are installed or rehabilitated in the same year are called cohorts. As they move along the time axis, they become older and reach the end of their lifetimes, in a manner determined by their ageing function. This time progression is simulated successively for all cohorts, year-by-year. The total length of drop-outs is summed and is defined as the rehabilitation need.

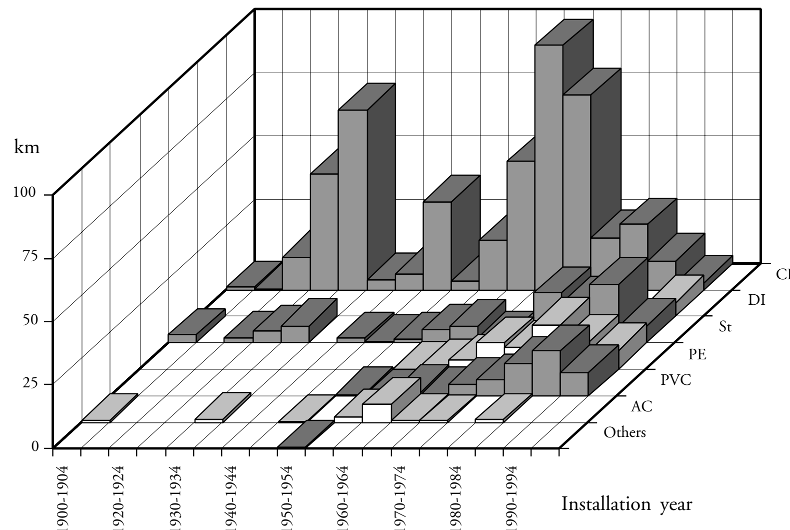

Fig. 2 Length of water mains in Teplice by period of installation and by material.

There are four ageing functions that are mathematically interrelated:

- lifetime probability function $f(x)$;
- survival function $1 - F(x)$;
- failure function $f(x)/(1 - F(x))$; and
- residual lifetime expectancy function $R(x)$.

The failure function is defined as the ratio of drop-outs among those which are still alive at age x. From this survival function, the expectancy of the remaining lifetime is derived as a conditional probability at age x. Ageing functions of the infrastructure elements can be described by different probability distributions, such as the uniform, normal, exponential, Weibull, and Herz distributions [6]. The latter of these has been used in the model applications to date because of its simplicity and the fact that the failure function initially increases in an exponential manner and then flattens to asymptotically approach a final failure rate for those remaining elements that do not deteriorate further as they get older. Ageing functions from the Herz distribution are shown in Fig. 3 for a set of ageing parameters.

The form of the ageing function depends on three parameters:

- ageing factor a,
- failure factor b, and
- resistance time c.

If $a = 0$, the Herz distribution turns into an exponential distribution with constant failure rates throughout the lifetime, so there would be no ageing in its proper sense. Failure factor b is the final failure rate at very old ages. Up to resistance time c, there is no rehabilitation, just a spot repair in the case. These ageing parameters can be tailored for specific situations.

RESULTS

At the present time, the model has been applied to 13 different European drinking water distribution networks and tested using KANEW in four USA water departments. The networks differed widely with respect to total pipe length, pipe materials, periods of installation, failure rates and the extent and technology of rehabilitation in the past.

Some utilities had difficulties in specifying the length of water mains by year, or the period of installation or category (material, diameter, joint, bedding quality), so the number of categories that were defined with respect to ageing behaviour and rehabilitation requirement varied widely, between 5 in Fort Worth, Texas, and 25 in Vienna. About a dozen categories would normally suffice. Although water mains of unknown composition or year of installation were quite common, this did not cause severe problems in general, because the data could be supplemented by intelligent estimates of sufficient accuracy.

It may be worth mentioning that, due to past rehabilitation work, the average network age varied between 28 and 71 years (Freiburg and Philadelphia, respectively), and the average residual lifetime expectancy of water mains in the networks differed by about 20 years when this was calculated using upper and lower bound survival functions.

Survival functions of water mains

It is difficult to forecast how long a particular water main will last. Models which estimate how many years it will take before the next failure occurs already exist [7]. They rely on failure records of particular pipes, and standard errors of this estimate are large, especially if the water main had no or few failures in the past. The decision to rehabilitate could be based on an economic analysis of the trade-off between cost savings by postponement and the increasing costs of repair [8].

Survival functions for categories of water mains are based on statistics of age-specific rehabilitation rates for older categories and on expert estimates for new products. Rehabilitation statistics are not only a function of failure rates, but also of past rehabilitation policies. They only generate a 'status quo'

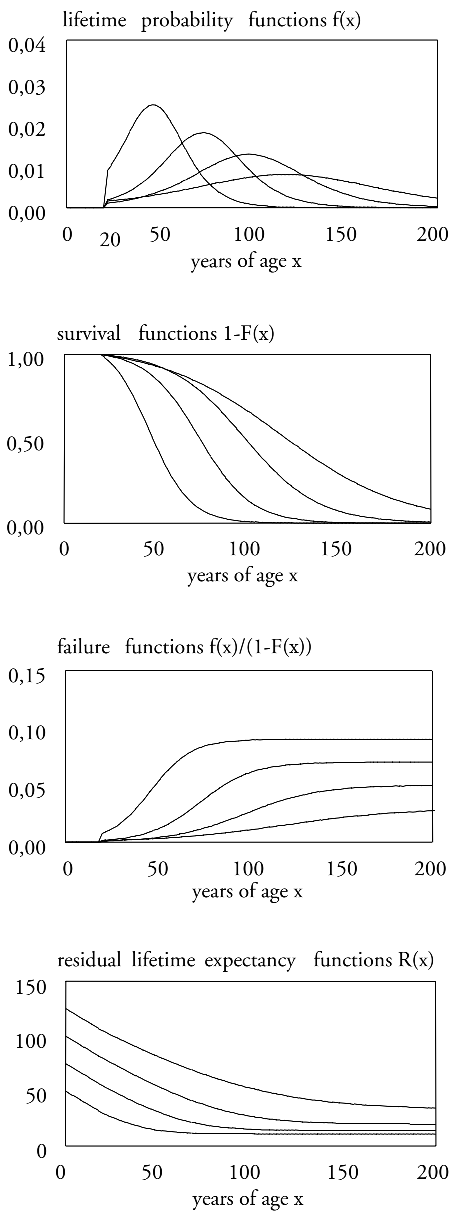

Fig. 3 Ageing functions from the Herz distribution with a resistance time of 20 years and lifetime expectancies of 50, 75, 100 and 125 years.

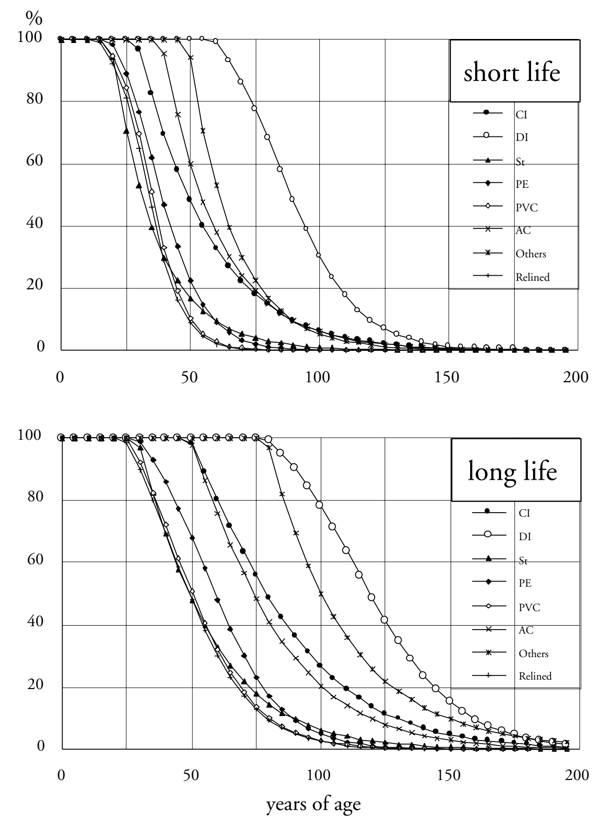

Fig. 4 Survival functions of types of water mains in the North Bohemian water supply system under more or less optimistic assumptions of their useful lifetime.

forecast if they are used for the calculation of future rehabilitation needs. However, taken together with failure statistics, they constitute a valuable source of information for estimating the lifetimes of water main types. There are always more or less optimistic estimates of lifetimes around a larger or smaller mean value, resulting in a range of survival functions (Fig. 4).

Survival functions with three parameters are determined by three points. For reasons of simplicity we recommend the taking of the following percentiles: the 50% (median) age, the 100% age of the resistance time up to which, according to the utility's rehabilitation policy, only spot repair is done, and as the third percentile, by way of example, the age attained by the most resistant 10% of a particular cohort. The closer the estimates of the median age and resistance time are, the steeper will the survival function fall off.

Future network rehabilitation needs

Annual network rehabilitation rates are arrived at from applying the rehabilitation functions of water main categories (corresponding to their particular survival functions), year-on-year, to the remaining stock. As the future rehabilitation needs of a given stock depend only on the lifetime estimates of its elements, the categories of water mains must be carefully defined with respect to their ageing behaviour. Lower and upper bound lifetime estimates lead to a range of rehabilitation needs, indicating the margins for an earlier or later appearance of these needs.

The rehabilitation needs of different networks can be compared if they are scaled in relation to the total length of their respective networks. Such annual network rehabilitation rates are presented in Fig. 5 for the Teplice water mains up to the

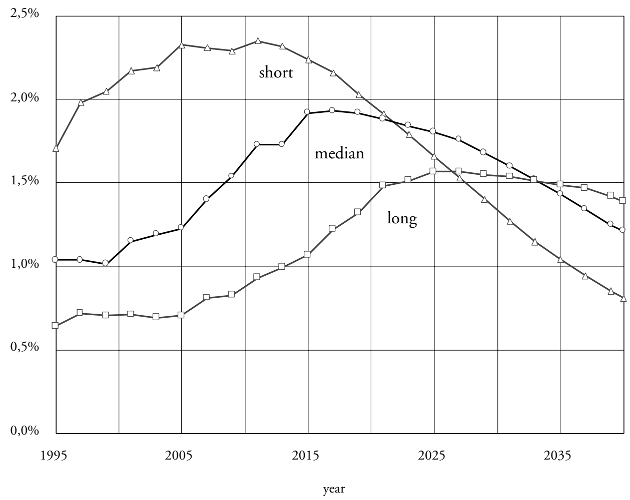

Fig. 5 Annual Teplice network rehabilitation rates under short, median and long pipe life assumptions.

year 2040, based on short, median and long pipe life assumptions.

Thus far, in most cases, lower bound lifetime estimates resulted in high rehabilitation needs in the short term. In some cases, the rates have been as high as 3.0–4.0% of the total length of the network, decreasing rapidly within a couple of years. This is an indication that rehabilitation needs have been postponed in the past. With more optimistic lifetime estimates, few utilities have revealed declining network rehabilitation needs in the short and medium term. Under these assumptions, most of them show rather low, and slightly increasing, network rehabilitation rates in the order of 0.5–1.0% per year. Although in general, higher rates are associated with older networks, rehabilitation also depends on the lifetime expectancies of water main types.

To some extent, these results can be reformulated by modifying the survival functions. However, limits are imposed by the estimates of lifetimes that other utilities have established for their water mains under specific local conditions. Significant deviations, in both directions, require justification. There is nothing wrong in modifying first-round assumptions after looking at the results they generate and the lifetime estimates of other utilities under their specific local conditions. Discussions amongst professionals about the useful lifetimes of particular types of water mains can also help to reduce uncertainty.

Network rehabilitation rates from the past are also quite informative. They vary a great deal from year to year, depending on the budget and on how costly the rehabilitation works were. A line can be fitted to the observations of past years, showing the intensity of rehabilitation and an increasing or decreasing trend. If this line points into the range of previously forecast rehabilitation rates (e.g. Zurich), the recommendation will just be to continue. The line may indicate that rehabilitation efforts should not be increased any further (e.g. Vienna). In many cases, however, there was a strong indication that rehabilitation activities were not sufficient, providing new arguments to engineers who had claimed for more.

Insufficient rehabilitation in the past is mostly associated with rehabilitation rates which are forecast to decline rapidly in the short term. There might also be an indication to recalculate the lifetime estimates of particular categories of water mains. However, the margin for such changes will not normally be large enough to conceal a neglect of rehabilitation.

EXPLORING NETWORK REHABILITATION STRATEGIES

There are many options open to water utilities that are searching for an appropriate long range network rehabilitation strategy, such as the extent of:

- rehabilitation vs. spot repair;
- replacement vs. relining;
- no dig vs. open ditch replacement;
- replacement alone vs. together with other public works;
- metallic vs. other pipe materials, and;
- area-wide vs. section-wise rehabilitation.

Any combination of these elements will have specific effects on the performance of the system in the short and long term.

With the cohort survival model it is possible to investigate the effects that different strategies will have on network performance indicators such as:

- frequency of failures;
- losses through leakage;
- age and residual lifetime expectancy.

While age and residual lifetimes can be calculated from the length of water mains in the system in a given year, failures and leakages have to be estimated on the basis of assumptions about the effectiveness of rehabilitation works. These tangible effects can then be transformed into cost and benefit figures and treated by the usual tools of economic analysis.

Rehabilitation vs. spot repair

While spot repair is a reaction to pipe failures, rehabilitation is proactive and will reduce future failures. As it cannot be exactly foreseen where and when failures will occur, spot repair is unavoidable. Spot repair is also less costly in the short term, so utilities prefer to go along with it, as long as they can justify it on economic grounds. Such a rehabilitation policy corresponds with upper range survival functions. However, when utilities are suffering from high failure rates due to delayed rehabilitation, they should use less optimistic survival functions, resulting in higher rehabilitation needs in the short term, because they will reduce failure rates more rapidly.

Rehabilitation technologies

KANEW forecasts the annual length of water mains, by category, that will reach the end of its life. In case of rehabilitation, this constitutes new cohorts of pipes with an ageing behaviour depending, for example, on whether the old pipes are replaced by fully protected new ones, or whether their life is merely prolonged by relining.

While relining is less costly, allowing more rehabilitation with a given budget, it may generate a secondary rehabilitation need in a future period of intensive rehabilitation.

Water main rehabilitation in combination with the reconstruction of gas pipes and urban roads certainly reduces their specific costs, but, in this case, the water mains will normally not be those that most urgently need rehabilitation with respect to failures and leakage. Water main replacement by 'no dig' technology makes a significant difference, but only if social costs are also taken into account.

Network performance indicators

The average network age is a widely used, although very approximate, indicator of the state of the network. It decreases rapidly if rehabilitation concentrates on the oldest water mains, which may not be those that are most failure prone. Water mains of a given age will have different residual lifetimes, dependant on their ageing behaviour. Therefore, residual lifetime expectancies are a better indicator for the state of the network than age, and it would be worthwhile to pursue the maintenance of an average residual lifetime expectancy in a network, and not to let it decline.

Rehabilitation work reduces future damages and leakage to an extent which can be calculated under the assumption that water mains, which had contributed substantially to these effects before rehabilitation, do not show any significant failures after rehabilitation, for some years at least.

Partial fulfilment of rehabilitation needs

The cohort survival model allows the relocation, year by year, of those water mains back into the existing stock which exceed a defined rehabilitation level. Therefore as they become one year older, their probability of failure increases accordingly, and additional failures must be covered by spot repair.

If a rehabilitation programme is severely cut, this will lead to an increase in the frequency of failures and in losses through leakage. Utilities may then redefine annual rehabilitation levels, for example by increasing the amount of low-cost rehabilitation, in order to cope with failure and leakage thresholds.

Capital value analysis

Network rehabilitation strategies should be based on long-term forecasts of effects. Investments come first, their effects later. Strategies can be evaluated in economic terms by discounting the streams of investment and revenue that they generate. Capital value analysis provides a tool for deciding which strategy is best, i.e. which shows the highest internal rate of return or the highest total capital value at the end of the forecasting period. It goes without saying that the decision should not rely purely on tangible monetary terms.

Quantifying annual rehabilitation costs is relatively easy with given unit costs and inflation rates. The same is true for savings of repair costs due to preventive rehabilitation. The quantification of savings from reduced water losses is more difficult, because the marginal cost is often unknown. Average costs per cubic metre of drinking water may lead to an overestimation of benefits from leakage reduction [9]. 20–30% of the total costs are considered to be the variable costs of drinking water production and distribution. But what about social cost?

CASE STUDY OF TEPLICE WATER MAINS

Teplice is one of nine water supply districts in Northern Bohemia, comprising 717 km of 7250 km of water mains in that region. In 1995, the rehabilitation needs of the total regional network were forecast using the cohort survival model on behalf of the SCVK Regional Water and Wastewater Authority [10]. The specific features of the subnetworks with respect to categories of water mains from different periods of installation led to significant differences in predictions of future rehabilitation needs. In spite of the considerable gap between the more and less optimistic views of the useful lifetimes of the various categories of water mains (Fig. 4), a rather more consistent pattern emerged on how to allocate the rehabilitation budget to the nine districts. Of course, this did not have the same per capita value for each district.

Definition of rehabilitation strategies

Following-up on this study, a case study was carried out in order to investigate rehabilitation strategies for the Teplice network. It was agreed that the network rehabilitation rate would have to be steadily raised from 0.2% in 1995 to at least 1.0% in 2010, with a corresponding annual increase in the rehabilitation budget. The following two strategies were defined:

- Strategy A: Replacement of old pipes by new ones;
- Strategy B: Two-thirds relining, one-third replacement of old pipes.

The rehabilitation budgets for the two strategies are the same, because in Teplice, relining is about half as costly as replacement. Thus in Strategy B, half of the budget will be spent on replacement, the other half on relining. Therefore in Strategy B the rehabilitation rate will increase from 0.3% in 1995 to 1.5% in 2010.

Suppositions

The effects of these two strategies have been simulated under the following suppositions, which are close to reality in the Czech Republic and particularly in Teplice:

- the network deterioration rate is 2% per year, initial failures and leakage rates are 0.5 failures per km per year and a leakage rate of 0.5 m^3 per km per hour
- the variable part of the water price is 1.5 CZK per m^3 and will increase by 8% per year due to inflation
- the rehabilitation cost is 1.6 mCZK per km for replacement and 0.8 mCZK per km for relining, and will increase by 5% per year due to inflation. The same will be the case for repair costs, which are 0.01 mCZK per failure
- replaced water mains had two failures per km per year and 2 m^3 of water losses per km per hour on average, which is fourfold the average figures for the network
- relined water mains had one failure per km and the same leakage rate as has been reported for replaced pipes
- as network failure and leakage rates improve, the factors of 4 and 2, respectively, are maintained, and rehabilitation measures become less effective
- after rehabilitation, water mains will have 0.1 failures per km per year and 0.1 m^3 of water losses per km per hour throughout the forecasting period, up to the year 2040;
- beyond the year 2010, rehabilitation strategies will proceed, however, to an extent forecast by KANEW.

As the Regional Water and Wastewater Authority of Northern Bohemia is primarily concerned with meeting the European water quality standards, it was agreed that the analysis of the two rehabilitation strategies would only take into consideration optimistic assumptions on the useful lifetimes of water mains, implying that higher failure rates would have to be accepted for the time being.

DISCUSSION

With assumptions of long mains life, Strategy A meets rehabilitation needs reasonably well, while Strategy B, with 50% more rehabilitation up to the year 2010, would do more than is needed, particularly with regard to cast iron pipes (Fig. 6). From 2020 on, Strategy B would generate secondary rehabilitation needs for relined water mains, which will then have to be replaced by new ones.

Both strategies will reverse the process of network deterioration, at least in the long term (Fig. 7). Strategy B is more efficient up to the year 2010, particularly with respect to leakage reduction.

The annual rehabilitation budget is planned to meet the linear increase in rehabilitation work up to the year 2010. So the two strategies do not differ in this respect. Beyond 2010, however, Strategy B is about half as costly as Strategy A. The cost savings from reduced repairs and water losses accrue cumulatively, and so they grow exponentially and

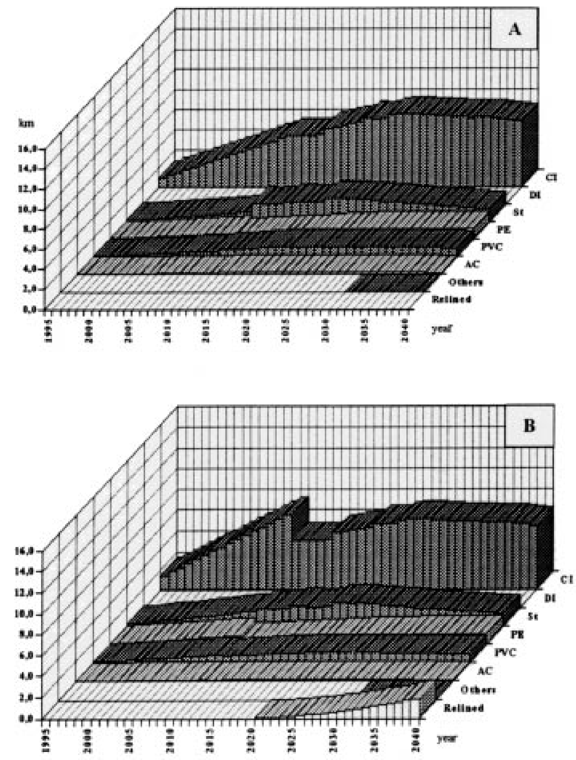

Fig. 6 Network rehabilitation mileage with long pipe life assumptions.

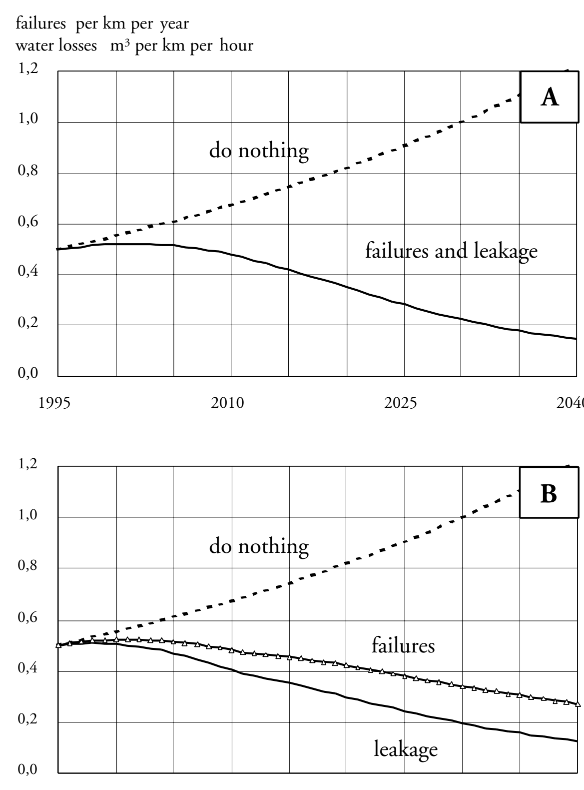

Fig. 7 Network failure, leakage rate and strategy forecasts.

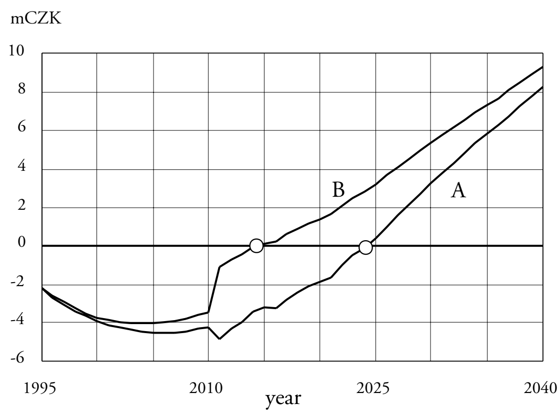

Fig. 8 Break-even years of rehabilitation costs and cost savings (in real terms) of strategies A and B.

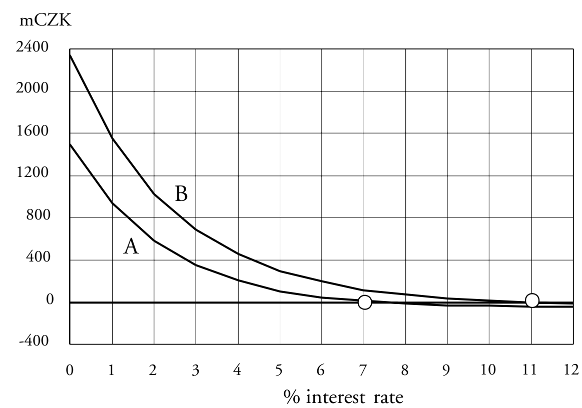

Fig 9 Internal rates of return of strategies A and B.

Table 1 Comparison of alternative strategies A and B

	2010 relative to 1995		2040 relative to 1995	
Decision criteria	A	B	A	B
Percentage rehabilitated	9%	13.5%	54%	58%
Average network age	+11 years	+9 years	+4 years	+3 years
Average residual lifetime	−2 years	−4 years	+30 years	+5 years
Reduction of failure rate	4%	4%	70%	46%
Reduction of leakage rate	4%	19%	70%	75%
Years to break even			29 years	19 years
Internal rate of return			7%	11%

will largely outweigh rehabilitation investment at the end of the forecasting period. The break-even year, when cost savings are equal to rehabilitation cost, occurs earlier with Strategy B than A (Fig. 8) and is not influenced by the inflation rate.

With inflation rates of 5% and 8%, respectively, rehabilitation cost and cost savings after 45 years will grow by such an extent that they will conceal any real effects. Costs and benefits that occur in the far future should be discounted with some social rate of preference. Whatever the interest rate, the internal rate of return differs for the two strategies. It is higher (and better) for Strategy B than A but must be seen in relation to the rate of inflation (Fig. 9).

Both strategies have their advantages and disadvantages. However, Strategy B should apparently be preferred on the grounds presented in Table 1.

Of course there are other factors that could and should be considered, such as the social cost, and the values of the decision parameters depend on the assumptions and suppositions stated above, which could change in the course of a more detailed analysis. However, this would be beyond the scope of this case study.

SUMMARY AND OUTLOOK

Future network rehabilitation needs can be simulated using a cohort survival model in a differentiated way, based on the explicit lifetime distributions of water mains under local conditions. More or less optimistic assumptions about the useful lives of water main types and their prolongation through maintenance and repair work results in rehabilitation needs occurring earlier or later and reducing network failure rates and leakage losses in different ways. With average and marginal unit costs, these positive effects can be transformed into monetary terms and compared with the rehabilitation costs. KANEW software [2] can provide an input for such an economic analysis. The programme is now being extended so that it can account for secondary rehabilitation requirements resulting from short-range, low-cost rehabilitation and for the delayed rehabilitation needs that result from budget restraints.

Responding to the interests articulated by its members, the Research Foundation of the American Water Works Association has sponsored the development of a user-friendly computer program for the quantification of future rehabilitation and replacement needs of water mains [2]. The German Association of Gas and Water Works has recently issued guidelines for rehabilitation planning for water distribution systems, which include the approaches described in this paper [11]. Similar guidelines will follow on gas networks. So there are good chances for utility managers to improve their rehabilitation policies and programmes in the near future.

BIBLIOGRAPHY

1 Herz RK. Alterung und Erneuerung von Infrastrukturbeständen—ein Kohortenüberlebensmodell, *Jahrbuch für Regionalwissenschaft* 1995; **14/15**: 5–29. French version: Degradation et renouvellement des infrastructures—un model de survie par cohorte. *Flux* 1996; **23**: 21–36.

2 Deb AK, Herz RK, *et al*. *Quantifying future rehabilitation and replacement needs of water mains*. Final report of AWWARF research project 265, AWWARF, Denver, 1998.

3 Herz RK. Ageing processes and rehabilitation needs of drinking water distribution networks. *J Water SRT—Aqua* 1996; **45**: 221–231.

4 Herz RK. *The impact of social cost on the rehabilitation needs of water distribution networks*. International NoDig'95 Conference Documentation, pp. 24–38. CCH, Hamburg, 1995.

5 Levine N. The construction of a population analysis program using a microcomputer spread-sheet. *J Am Inst Planners* 1985; **51**: 496–511.

6 Trujillo Alvarez R. *Bedarfsprognose und Strategieentwicklung für die Rehabilitation städtischer Wasserrohrnetze*. Schriftenreihe des Instituts für Städtebau und Landesplanung (ISL), Universität Karlsruhe, 1995.

7 Andreou SA. *Predictive models for pipe break failures, their implications on maintenance planning strategies for deteriorating water distribution systems*. PhD thesis MIT, Cambridge, 1986.

8 Shamir U, Howard CPD. An analytic approach to pipe replacement. *JAWWA* 1979; **71**: 248–259.

9 Herz RK, Hruza P. *Rehabilitation Needs of the Vienna Water Supply Network, Water Saving Strategies in Urban Renewal: European Approaches*, pp. 105–124. European Academy for the Urban Environment, Dietrich Reimer, Berlin, 1997.

10 Herz RK, Trujillo Alvarez R. *Future rehabilitation needs of the drinking water distribution network of Severoceske Vodovody a Kanalize a.s (SCVK)*. Unpublished study on behalf of SCVK ISL, Karlsruhe University, 1995.

11 Mayr H, *et al*. *Entscheidungshilfen für die Rehabilitation von Wasserrohrnetzen*. DVWG Hinweis W 401, Bonn, 1997.