Developing Rehab Strategies For Drinking Water Networks

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Summary: Urban drinking water networks come at age and need more and more rehabilitation. These needs are largely determined by the length of pipes which have been laid into the ground during past decades with different materials and technologies. There is empirical evidence from failure and rehabilitation statistics that particular pipe types have specific service lives. Thus service life distributions can be applied in a cohort survival model for a differentiated annual forecast of the mileage of pipes reaching the end of their service life and, therefore, being in need of rehabilitation in a particular year.

Within the bands of future rehabilitation needs, medium range programs can be designed defining annual targets for specific pipes to be rehabilitated with new materials and technologies. The cost of such rehab programs must be evaluated with respect to their long term effects. Whereas annual rehab investments are derived from specific unit costs, cost savings and other benefits from rehabilitation, during the program period and beyond, are more difficult to forecast. The rehab program may have insufficient effects with respect to reducing failures and leakage and enhancing network service reliability. Some of these effects can be expressed in monetary terms and evaluated with dynamic investment methods in a cost benefit framework.

This paper presents a framework for exploring network rehab strategies and describes the method for forecasting the effects of specific rehab programs. A cohort survival model with specific aging functions is linked to a simulation model which calculates the effects of advanced or postponed rehabilitation on some network performance indicators such as failure and leakage rate and average residual life expectancy of pipes in the network. Based on these results, a multi-criteria evaluation procedure is presented for choosing the best rehab program from a set of alternatives. The case of an East German water utility shows how this general approach has been applied for developing a medium term rehab strategy for a the network of water mains.

Keywords. Drinking water network, rehabilitation, service life of pipe types, strategic investment planning

1 INTRODUCTION -NEED FOR LONGER VIEW ON INFRASTRUCTURE REHABILITATION

Most water utilities have not developed a long-term rehabilitation strategy, nor do they systematically explore their options for maintaining or upgrading the water distribution network. Usually they decide on a year-to-year base which elements of the water supply system should be rehabilitated. At best, a list of most urgent rehabilitation projects is established and work proceeds along this list of projects that are “in the pipeline” as long as there are funds available and the budget is not cut by other investment needs such as for the supply of new building developments or the repair of unforeseen pipeline damage.

This procedure allows flexible response to whatever comes up, and to some degree, of course, water utilities will always use this re-active “fire brigade” approach, not only because of our limited forecasting capabilities. However, there is a large potential for reducing this “muddling through” and for improving the efficiency of water network rehabilitation. Network information systems, which have been installed in all major water utilities by now, provide a rich source of information which should be used in a pro-active approach to network rehabilitation. Research is under way on this subject (Saegrov et al. 1999, Baur,Herz 1999) in Europe, for example within the CARE-W project, in North America in projects sponsored by the AWWA Research Foundation, and at NRC CNRC (Rajani,Kleiner 2001), and in Australia at CSIRO (Burn 1998) and the home of the Nessie model.

There are bottom up and top down approaches to rehabilitation planning, bottom up starting from individual pipelines, top down starting from the network level. Both approaches need research on the aging behaviour of pipes. Failure forecasting and decision making on whether to go on with spot repair or to do major rehabilitation work, should account for the characteristics of individual pipelines, whereas budget forecasting for maintenance and rehabilitation investments may be sufficiently based on the average aging behaviour of types of pipelines in the network. The network level, in general, seems to be more appropriate for long-term asset management decisions, whereas operational short-term decisions should be based on more detailed information.

Due to our limited forecasting capabilities, some features of the water supply system must be analysed post factum. Water quality for example is monitored and controlled by regular sampling to guarantee that standards are fulfilled. Network performance indicators such as the frequency of bursts, service interruptions, head loss and pressure deficiencies and leakage can be quantified from annual operational statistics and forecast in the short run at least. They indicate whether specific targets of network performance, set by the water utility, are met or need further efforts. Once these targets being set, the utility management is observing how the indicators change and, with some notion on the effectiveness of certain measures, steering the system towards these targets.

The longevity of infrastructure requires a longer view in setting targets of network performance and in developing network rehabilitation strategies. Even the decision of replacing an old pipeline now or postponing its rehabilitation for another year, has to take a long view: At what rate will bursts and leakage increase, what damage will they cause, how long will the new pipeline be in service after rehabilitating the old one? Investments for network improvement need economic justification in a comprehensive cost-benefit framework covering the whole service life of the pipeline.

The result of such an economic analysis depends very much on the full costs of replacement or renovation of pipelines on the one side, and on all direct and indirect benefits resulting from reduced leakage and failures on the other side. These benefits are a function of the water tariff, the damage caused by pipe failures and the repair costs. While investment costs accrue at the beginning and are evenly distributed over a defined financing period, benefits from reduced leakage and repair extend over a longer period and tend to diminish towards the end of the pipe’s service life.

As the benefits from rehabilitation accrue over the whole life of a pipeline, rehabilitation strategies should be explored in the long range, even if they are implemented only in the short or medium range. There is a wide variety of options for doing more or less rehabilitation sooner or later, in a more or less costly way, providing shorter or longer service lives, and there is always the do-nothing alternative: no investments into renovation or replacement, just spot repair of burst pipes.

In the following a framework is presented for exploring rehabilitation strategies with respect to their long range effects. This framework has been applied to many water and gas distribution networks in Europe and USA. It is based on a cohort survival model for infrastructure networks (Herz 1996), which will be briefly presented thereafter. Further methodological details and results will be given in the subsequent illustrative example produced with KANEW, a software developed in a AWWA-RF project (Deb et al.1998) and being further advanced in CARE-W.

2 FRAMEWORK FOR EXPLORATION OF WATER NETWORK REHAB STRATEGIES

Future rehabilitation needs are largely determined by the present stock of pipes in the network that have been laid in specific periods with particular materials and technologies (Fig.1). Statistics reveal that some of them have higher failure rates at younger age and have been rehabilitated earlier than others. This allows to identify types of pipe with different aging behavior and to estimate their service life under more ore less favourable conditions. These service life distributions can be expressed by mathematical functions and used in a cohort survival model (see next section) to forecast network rehabilitation needs. The cohort survival model can be used to generate a range of future rehabilitation needs under more or less optimistic assumptions (Herz 1998).

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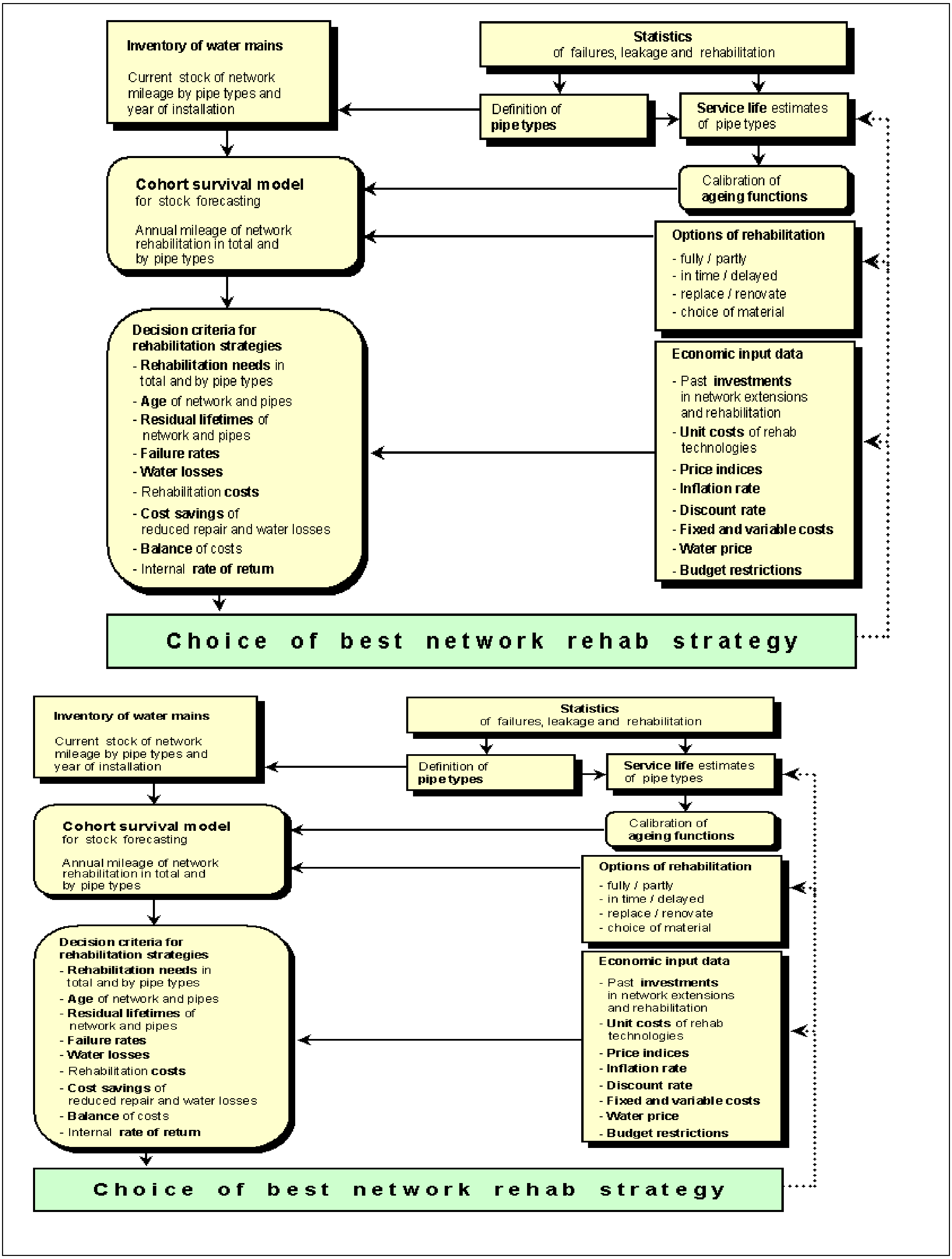


Figure 1. KANEW framework for the exploration of network rehabilitation strategies

The band of rehabilitation needs forecast by the cohort survival model for particular pipe types helps to define alternative rehabilitation programs. According to the rehabilitation program specified, the pipes that reach the end of their service life are rehabilitated, the others remain in the stock, get older and continue to deteriorate. The number of failures drop for the rehabilitated pipes whereas they increase for the others. So several decision criteria can be calculated year by year and expressed in economic terms by specific unit costs as shown in Fig.1. This allows to balance the costs and benefits of alternative rehabilitation programs. Because rehab investments come first and benefits later, accumulating over the service life of the new pipe, internal rates of return are calculated by discounting the costs and benefits of each rehabilitation program.

The best rehabilitation program will be found interactively by comparing systematically advantages and disadvantages of alternative programs and by generating new alternatives that come closer to the desired targets under budget restrictions.

3 A COHORT SURVIVAL MODEL FOR INFRASTRUCTURE DETERIORATION

The cohort survival approach stems from demography, where cohort survival analysis is widely used to forecast population changes from mortality and fertility statistics. Failures of infrastructure correspond to mortality and lead to rehabilitation. They tend to increase with age. Only some very old elements seem to last for ever. In an infrastructure survival model, types of elements installed or rehabilitated in the same year are called cohorts. As they move along the time axis, they get older and reach the end of their lifetimes according to their specific aging behavior. In cohort survival models, this progression in time is simulated successively for all cohorts year by year. Elements of infrastructure that have reached the end of their service life, usually are replaced, renovated or upgraded, constituting a rehabilitation need at a particular point in time.

This can be expressed in mathematical terms on the basis of Weibull, Gumbel and Herz distributions [Kleiner,Rajani 1999]. There are four types of aging functions that can be derived from these probability distributions:

- lifetime distribution function $f(x)$,
- survival function $1 - F(x)$,
- momentary failure/rehabilitation rate function $f(x) / (1-F(x))$ and
- residual lifetime expectancy function $R(x)$.

The lifetime distribution $f(x)$ is a probability density function defined for positive values of age x. It is usually bell shaped or skewed to the left. By definition, “infant mortality” of infrastructure elements is excluded as a matter of guarantee. For types of infrastructure that have been laid decades ago, lifetime distributions can be derived from statistics on the age of particular elements at the rehabilitation date. However, due to financial and technological changes, these statistics of past cohorts do not necessarily hold for the future. For new types of infrastructure, there is very little empirical evidence how long they will last.

Survival functions are derived from the cumulative $F(x)$ of the lifetime distribution. The percentage of elements of a cohort that reaches a particular age can be read from survival functions for specific types of infrastructure.

The rehabilitation rate of a cohort at a particular age is relating the elements that reach the end of their service life at a particular age to those that have survived so far. This rate is particularly useful in the simulation program because the stock of infrastructure is updated year by year. Again neglecting infant mortality of infrastructure elements, the rehabilitation rate starts from zero and gradually increases with age. A special feature of the Herz distribution (Herz 1996a,b) is that the rehabilitation rate is increasing progressively up to the median age, then turns into a degressive increase and finally approaches asymptotically a maximum rate. This means that the most resistant very old elements slow down their deterioration.

The residual lifetime expectancy starts from the mean value to decrease linearly at first, then degressively until it approaches a finite value close to zero, leaving some hope for survival. This results from the asymptotic behavior of the rehabilitation rate in the Herz distribution.

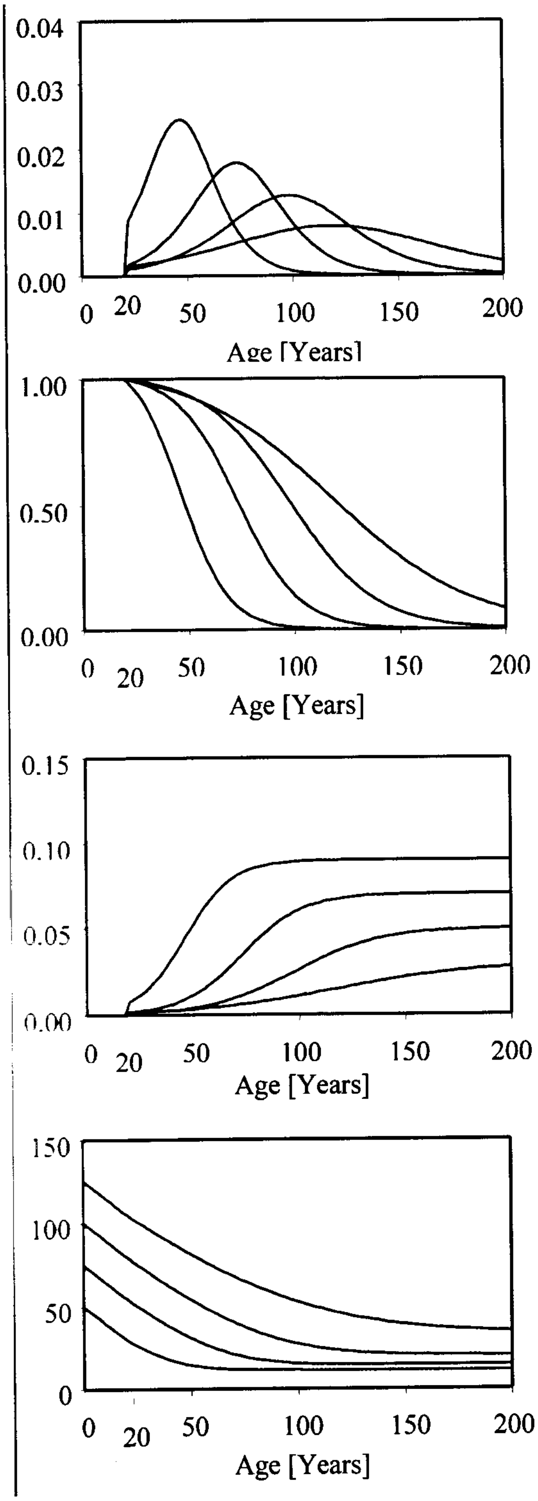
The Herz distribution is implemented in the KANEW model. It allows to calibrate specific aging functions for particular types of infrastructure by setting specific values for three aging parameters:

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

The aging factor a describes the smoothness of the starting phase of the aging process. The larger this value is, the smoother the aging process starts. For $a = 0$, the Herz distribution turns into the exponential distribution, which is not appropriate for describing the aging process of infrastructure elements because the failure rate starts abruptly and remains constant over the lifetime of the cohort.

Failure factor b is the final failure rate at very old age.

Up to resistance time c, there is no rehabilitation, just spot repair in case.



Lifetime distribution

$$f(t \le c) = 0$$

$$f(t > c) = \frac{(a+1)b\exp[b(t-c)]}{(a+\exp[b+(t-c)])^2}$$

$$f(t = \infty) = 0$$

$$E(t) = c + \frac{(a+1)\ln(a+1)}{ab}$$

Survival function

$$1 - F(t \le c) = 1$$

$$1 - F(t > c) = \frac{a+1}{a+\exp[b(t-c)]}$$

$$1 - F(t = \infty) = 0$$

Failure/renewal rate

$$z(t \le c) = 0$$

$$z(t > c) = \frac{b\exp[b(t-c)]}{a+\exp[b(t-c)]}$$

$$z(t = \infty) = b$$

Residual lifetime expectancy

$$E(\tau/t \le c) = c - t + \frac{(a+1)\ln(a+1)}{ab}$$

$$E(\tau/t > c) = X\frac{\ln X}{ab} - \left(\frac{t-c}{a}\right)$$

with $X = a + \exp[b(t-c)]$

$$E(\tau/t = \infty) = b^{-1}$$

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

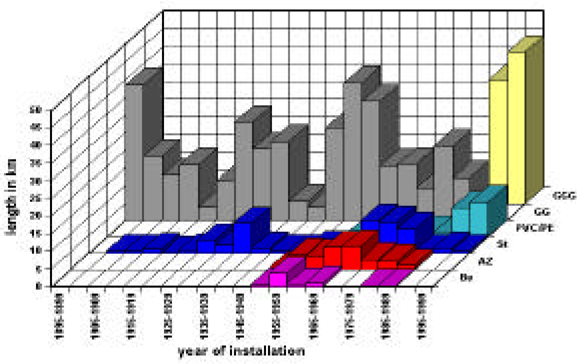
4 RESULTS FROM A GERMAN CASE STUDY

The water supply system of a city in East Germany is serving as an example to illustrate how future needs of network rehabilitation are forecast with KANEW and what the long term effects of a specific rehabilitation strategy will be. Although this case study is using data from a particular network and economic parameters which are typical for the German situation in general and this municipal water company in particular, some attempts are made to generalize this case study as much as possible.

4.1 Present situation

The water supply system is serving about 160, 000 people through 550 km of water mains plus 250 km of service pipes. Service pipes lie within the responsibility of the property owners. Water consumption of households plus industry is about 170 l/p·d. Before the German re-unification it was twice as much. About one third of the water fed into the system is non-revenue water, amounting to water losses in the order of 1 m³ per hour and km of water mains. Probably about two thirds of these water losses are due to bursts, leakage at cracks, corrosion holes, joints, valves and hydrants. The failure rate (with water extrusion) is about 0.55 per km and year for water mains and 2.35 for service pipes. So almost half of the leakage may occur on service pipes. These figures are significantly higher than the average for East German water distribution networks, which again is about twice as high as the West German average.

The future need of network rehabilitation depends on the aging behavior of the existing stock. In the following we concentrate on water mains (Fig. 3). Two thirds are cast iron (GG) pipes, most of them older than 50 years. After German re-unification, almost one hundred km of new ductile cast iron (GGG) pipes and some PE pipes have been laid. In addition to cast iron pipes, there are also some older steel (St), asbestos (Az) and concrete (Bs) pipes approaching the end of their service lives. During the last decade, almost 2% of the network has been rehabilitated per year, mostly by replacing old cast iron and steel pipes. There has been little cement-mortar relining of old cast iron pipes although most of them show heavy incrustation, but there were no problems with discolored water.

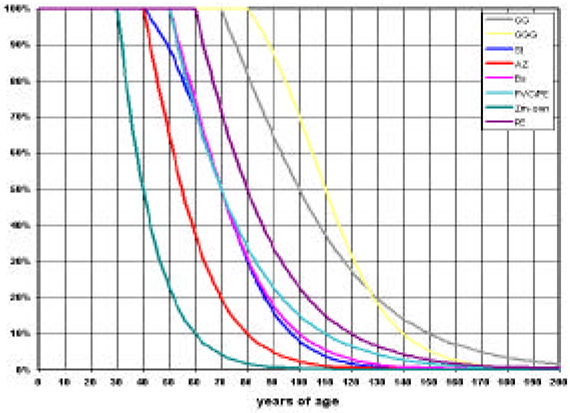


Seven categories of water mains are shown by 5-year periods of installation. Further distinctions could be made for pit cast iron and gray iron and for steel pipes of different quality and anti-corrosive protection. As there are always some pipes of unknown age and/or material, they may be assigned at best guess without causing major distortions to the calculation of future rehab needs.

Figure 3. Length of water mains by period of construction and by material

4.2 Aging behaviour of pipe types

Pipe age alone cannot justify rehabilitation. However, age in combination with other characteristics of the pipe can be used to produce reasonable and consistent estimates of the service life of types of pipe (Fig. 4). Based on local experience and on the analysis of failure and rehabilitation statistics, ranges of age are estimated that would be reached by 100, 50 and 10 % of a particular type of pipe under more or less favourable circumstances. Usually this is done in an interactive way including research, engineering and management staff of the particular water supply company. For new types of pipe, the Delphi method is applied. Survival curves from other water utilities give some orientation.



As a rule, most water utilities do not replace a pipeline before it reaches a certain age. Up to this age, in case of a failure, there will be spot repair, no thorough rehabilitation. This age threshold varies with pipe material. Ductile iron pipes are assumed to be more resistant and to get older than cast iron and PE pipes. Renovation with cement mortar relining will prolong the service life of a pipeline under optimistic assumptions by 40 plus minus some years, for 10 % of them even by 60 years.

Figure 4. Survival functions of types of water mains under optimistic service life assumptions

The results of the cohort survival model depend very much on the estimates of specific service live distributions or survival functions. Therefore, simulation runs are performed by KANEW with lower and upper bounds and with median survival functions in order to delimit the range of future rehabilitation rates (Fig. 5).

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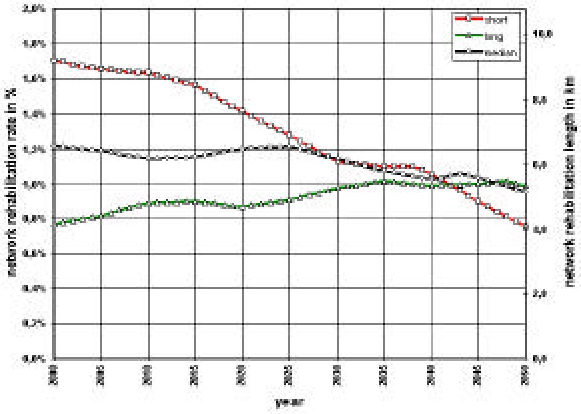


Short service life assumptions lead to earlier and larger rehabilitation rates. In this case, they start with values that are about twice as high as those based on upper bound service life assumptions. With median service life assumptions, network rehab rates decline from 1.2 to 1.0 %. In most cases, pipe construction periods in the past result in pronounced peaks in the future. Quite often, particular types of pipes create specific peaks of rehab needs.

Figure 5. Annual network rehabilitation rates assuming short, median and long pipe lives

4.3 Defining rehabilitation programs

The forecast rehabilitation needs give some orientation for the rehabilitation program. In this case, the rehabilitation rates of 2% of the past decade would not be needed any more, even under pessimistic assumptions on the service life of the pipes. However, for the future rehabilitation program there are many options with different consequences. More or less pipes of a particular type can be rehabilitated more or less thoroughly earlier or later. This decision should be taken in the light of the effects that can be expected from specified rehabilitation measures, such as financial consequences and effects on burst and leakage rate, social cost, reliability of service, value of assets and, ultimately water tariff.

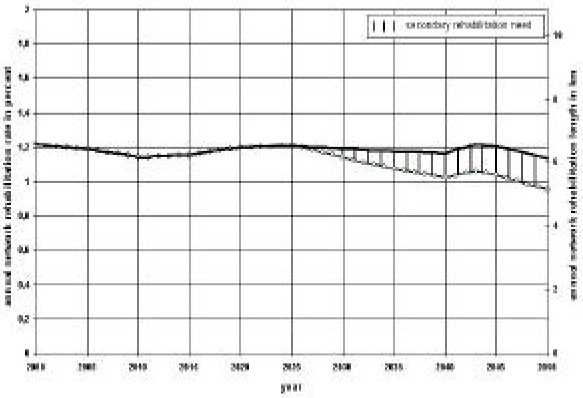
KANEW allows to specify annual rehabilitation rates for types of pipe within the rehabilitation period and, beyond this program horizon, calculates the over- or unfulfilled rehabilitation need of types of pipe up to time horizon of the analysis.

For this case study, a rehabilitation program was defined and tested that fulfils the network rehabilitation rate forecast on the basis of median service life distributions of types of pipes. In this rehabilitation program it is assumed that 20% of cast iron and steel pipes will be renovated, 60% will be replaced by ductile iron and 20% by PE-pipes. Old PVC/PE-pipes will be replaced by new more resistant PE pipes, concrete pipes by ductile iron pipes of larger diameters. 60% of asbestos pipes will be replaced by ductile iron, 40% by PE-pipes.

4.4 Forecasting the effects of a rehabilitation program

4.4.1 Secondary rehabilitation needs

Any rehabilitation program will generate, on the long run, secondary rehabilitation needs from pipes which will rehabilitated in the future. This fact can be neglected for new pipes because they will need rehabilitation far beyond the time horizon of this analysis. However, pipes renovated by cement mortar relining will not last that long. The life of the old pipe is extended only by 30 to 40 years on the average. So within the forecasting period, renovated pipes will generate an additional secondary rehabilitation need which has to be taken into account. This secondary rehabilitation need cannot be fulfilled by another renovation. Thus, in line with the other specifications of this rehabilitation program it is assumed that 60% of these pipes will be replaced by ductile cast iron and 40% by PE-pipes. With median service life assumptions, this replacement process of renovated pipes starts after 25 years, and the network rehabilitation rate is increasing accordingly (Fig. 6).

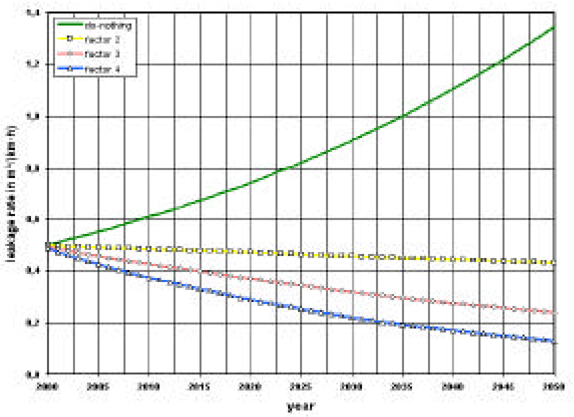


Renovated pipes are assumed to survive at least 20 to 30 years (see Fig.4). Under median service life assumptions, half of them will reach an age of 35 years. So, in the year 2025 these renovated pipes start to create a secondary rehabilitation need, which is fulfilled by replacement. Thus low cost rehabilitation has a significant long term effect, in this case increasing network rehabilitation rate by 20% in 2050.

Figure 6. Annual network rehabilitation rates under median pipe life assumptions including secondary rehabilitation needs of renovated water mains

4.4.2 Leakage reduction

The leakage reduction resulting from this rehabilitation program is simulated by assuming that the new pipes will have minimal leakage rates of 0.01 m³ per km and hour which will increase by 2% per year. In the starting year 2000, the average leakage rate of water mains is 0.5 m³ per km and hour. The higher the rehabilitation rate, the more leakage is reduced.

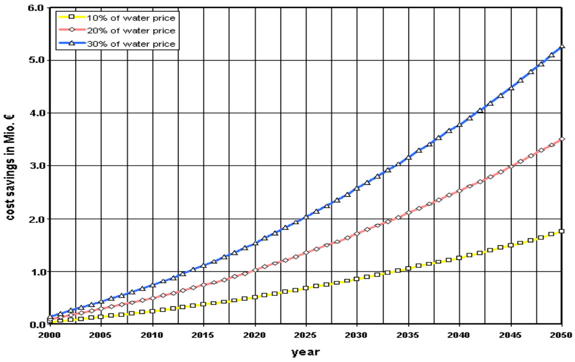


In the do-nothing alternative it is assumed here that leakage will increase annually at a constant rate of 2% on the average. Rates could be differentiated according to types of pipes. Rehabi-litation will reduce leakage to the extent of old leaky pipes being replaced by new and tight ones. Leakage reduction also depends on the efficiency of selecting the most leaky pipe-lines for rehabi-litation as expressed by a rehab efficiency factor related to the current network leakage rate.

Figure 7. Leakage rates for do-nothing alternative and rehabilitation according to median service lives

Leakage reduction also depends very much on how successful the network operators are in picking the most leaky pipelines for rehabilitation. When water mains are replaced in an integrated street reconstruction project including utility lines, leakage before replacement may be just about average. Rehabilitation programs that are especially designed for leakage reduction will select the most leaky pipelines. Empirical evidence from the water utility of the city of Chemnitz [Müller 1999] showed that water mains had leakage rates of about 3 times the network average before rehabilitation. This can be taken into account by a corresponding rehab efficiency factor. In order to show the effect of different rehab efficiency factors, the simulation model was run with rehab efficiency factors 2, 3 and 4 (Fig. 7). Note that this simulation shows only to leakage reduction from pipe rehabilitation. Spot repair of leaky pipes, possibly detected by special leakage reduction squads, will be more efficient in this respect, particularly for networks with high leakage.

The cost savings from leakage reduction depend on the quantity of saved water and its unit prize which is not the water rate(Herz,Hruza 1997). The results shown in Figure 8 are based on the defined rehabilitation program and a rehab efficiency factor of 3. In general, water prevented from leaking out is worth less than if it is sold to customers because most of the production cost are fixed interest and personnel costs. Cost savings are marginal costs accruing from the variable unit costs of water production. Only exceptionally, when leakage reduction allows to close an existing production unit or to avoid the construction of new one, marginal cost savings will be higher than variable costs. Without information on marginal cost in this particular local situation, the share of variable costs is taken for marginal pricing of leakage reduction. The local water price, which covers the fixed and variable costs of water supply, is 2 €/m³ in the year 2000 and is estimated to rise by 1% per year.



As leaky pipes are replaced year by year, and have only minimal leakage in subsequent years, the volumes of saved water accumulate year by year. They are valued by the variable part of the water price (10, 20, 30%) as a proxy for the marginal costs of saving water. This part of the water price covers only those cost elements which are directly related to the quantity of sold water.

Figure 8. Cost savings from reduced water leakage for different marginal costs

4.4.3 Reduction of failures and repair

In addition to cost savings from reduced leakage, benefits accrue from reduced repair work on new pipelines in particular and on renovated ones as well. The effect on failure reduction is simulated in the same way as for leakage reduction. It is assumed that pipelines with relatively high failure rates are chosen for rehabilitation and that new pipelines will have a failure rate of 0.01 and renovated ones 0.1 failures per km and year increasing by 2 % per year.

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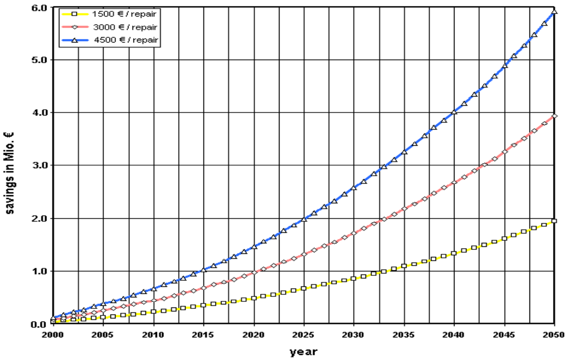
In this case study, the starting failure rate for water mains is 0.55 failures per km in the year 2000. Failures are assumed to increase annually by 2 % if no rehabilitation measures were taken and failure prone pipelines to be chosen with an efficiency factor of 3.

Average repair cost is 1500 € per failure at present and assumed to rise with 1.5% per year. This figure should cover all direct costs of the water utility, including the fees paid to the insurance company for compensation of damage caused by pipe failures. However, it certainly does not include external costs of service interruption, traffic congestion due to burst pipes and repair work in the street, noise and dust emission on passengers and neighbors nor compensation for temporary sales reduction in adjacent shops and services. These indirect, external or social costs are usually taken into account by applying factors to the direct costs.

In this example, social cost factors of 2 and 3 are applied in order to show the effect (Fig. 9).

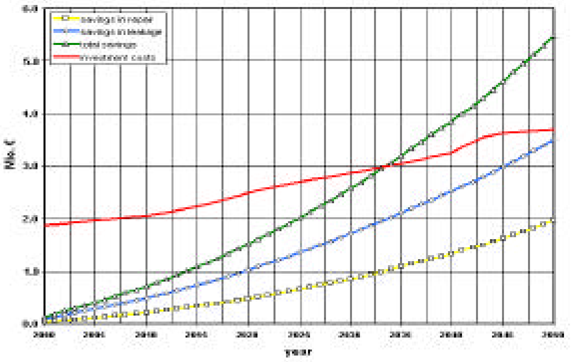


As new pipes have minimal failure rates in subsequent years, repair cost savings accumulate in a progressive way. Whereas the water utilities cover only the direct costs, the public may be concerned with the indirect “social” costs which are associated with repair work in the streets. Social cost factors of 2 and 3 times the direct costs show corresponding effects on the benefits from savings in repair costs.

Figure 9. Cost savings from reduced failures for different social cost factors

4.4.4 Rehab investments

Annual rehab investments are calculated by multiplying the annual pipe replacement and renovation with their specific unit costs. In this case, the unit costs for replacement are 300 € per meter of ductile iron pipes and 275 € for PE-pipes. The unit cost for cement mortar relining is 225 €/m. Prices for pipe work are assumed to rise by 1.5% per year. With these economic data, the annual investment costs and benefits of this particular network rehab program can be presented up to the year 2050. The benefits shown in Figure 10 are calculated with an efficiency factor of 3. Reduction of leakage is valued with a marginal cost of 20 % of the water price, and reduction of repair is only for direct costs.



Annual rehab investments increase rather steadily up to the year 2050. The benefits from savings in leakage and repair costs accumulate and surpass rehab investments in the year 2036. Beyond the year 2050 no further rehab investments are considered, whereas benefits from past rehab investments will continue to accrue, although in a decreasing manner.

Figure 10. Annual rehab investments and cost savings from reduced water leakage

4.4.5 Comparing costs and benefits

As can be seen from Fig. 9, for this particular rehabilitation program, the benefits from cost savings in leakage and repair are reaching the same order of magnitude as the rehab investments. There is a time lag and a cumulative effect of benefits. In this case, savings from reduced leakage contribute more than those from reduced repair. This depends on the marginal cost of water leakage and the unit cost of repair. Up to the year 2035, rehab investments are higher than the cost savings. The year 2036 could be called “break even year”. Thereafter, benefits from savings are larger than the costs of rehab investments. It should be noted that the benefits from rehab investments extend beyond the year 2050 by the service life expectancy of rehabilitated pipelines, particularly ductile cast iron pipes, which this are assumed to last 100 years on the average.

Benefits which occur in the far future do not have the same weight as costs which accrue in the next years. Therefore, costs and benefits are discounted into present values. As the present values of costs and benefits depend heavily on the discount rate (see Fig. 11), internal rates of return are calculated for which the discounted benefits are equal to the discounted costs. Due to the fact that rehab benefits extend beyond the period of investment, there are significant net benefits at low discount rates. Rehab

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investments pay off as long as future net benefits are discounted with rates beyond the internal rates of return. In general, it is recommended that the internal rate of return should be at least 3% larger than the inflation rate. Thus the rehab investments of the given example would pay off.

The higher the marginal costs of water losses, the larger are the present values of the discounted net benefits and the internal rate of return. Investments pay off if the internal rate of return is larger than the inflation rate. In this case, annual inflation was assumed to be 1.5% for pipe works, which is significantly lower than the internal rates of return for savings in direct repair costs and leakage valued at 10 to30% of the water price.

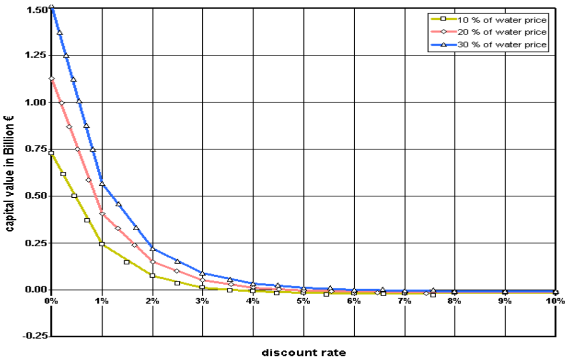

Figure 11. Internal rate of return for rehab investments with median service lives

5 CONCLUSIONS AND OUTLOOK

The aim of this paper was to show how the long-range effects of specified rehabilitation programs can be analyzed in a comprehensive cost benefit framework and used to develop an "optimal" network rehabilitation program. The process of network deterioration and the effects rehabilitation needs that are not fulfilled in due time, were calculated with a cohort survival model. With this model, as implemented in the KANEW software, several network performance indicators were forecast year by year and expressed in economic terms. Assumptions have to be made for such long term forecasts and economic evaluation. The sensitivity of the results with respect to the uncertainty of specific assumptions is shown for an illustrative example of an East German water supply system.

Some general conclusions may be drawn from this study. In the first place, such long-term projections appear to be a useful complement to the "fire brigade" and monitoring approaches prevailing in water supply network management. In spite of our limited forecasting capabilities, the band of rehabilitation needs can be determined by a cohort survival model for specific types of pipes in the near and far future. Cohort survival models are implemented in KANEW, WARP and the Nessie Model. Such models should be used for water company asset management.

Second, rehabilitation programs for a period of 5 to 10 years should be developed after looking at the effects they are expected to have in the short, medium and long run. In the short run they will not pay off, because the benefits extend and accumulate over the whole service life of the rehabilitated pipes. However, the intensity of rehabilitation work that can be justified in economic terms varies considerably with the present state of the network, the water rate and the direct and indirect costs of repair and rehabilitation. With low water prices and cheap repair of broken pipes and leaks, rehab investments will not pay off, even in the long run, if external costs of pipeline failure and repair are not included. These so-called social costs, which are difficult to quantify in general, enlarge the benefits from rehabilitation (Herz 1995, Baur,Herz 1999).

Third, due to the large number of network rehabilitation options, an "optimal" rehabilitation program has to be developed in an interactive way by modifying those parameters that lead to undesired results. This implies a formal procedure by which the outcome of alternative rehabilitation programs is systematically compared with each other. Such a multi-criteria evaluation procedure is being developed in the CARE-W project.

The approach presented in this paper is a top down approach, which is recommended for strategic investment planning and asset management. The focus is on the network, not on individual pipes within the network. The efficiency of a network rehabilitation program depends very much on the efficiency of the individual pipeline rehabilitation projects included in the program. So, in a top down approach, the next step of selecting the most cost-efficient rehabilitation projects is a very important one. Research is under way on this subject in CARE-W as well (Baur/Kropp 2001).

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7 REFERENCES

1. Baur, R., Herz, R.K. eds. 1999, Service Life Management of Water Mains and Sewers. Decision Criteria and Strategies for Rehabilitation. Proc. 13th Junior Scientist Workshop, Dresden.
2. Baur, R., Kropp, I. 2001, 'Selecting and scheduling infrastructure rehabilitation projects', Proc. of IWA World Water Congress, Berlin.

3. Burn, S. 1998, Optimisation of Pipeline Rehabilitation Scheme, Proc. 2nd Int. RILEM Conf. on Rehabilitation of Structures, Melbourne, pp. 258-266.
4. CARE-W, in www.unife.it/care-w
5. Deb, A., Hasit, Y.J., Grablutz, F. and Herz, R.K. 1998, Quantifying future rehabilitation and replacement needs of water mains, AWWA Research Foundation, Denver.
6. Herz, R.K. 1995, ‘The impact of social cost on the rehabilitation needs of water distribution networks’, Proc. International NoDig’95 Conference, CCH Hamburg, pp. 24-38.
7. Herz. R.K. 1996a, ‘Dégradation et renouvellement des infrastructures: un modèle de survie par cohorte’, Flux 23, pp. 21-36.
8. Herz, R.K. 1996b, ‘Ageing processes and rehabilitation needs of drinking water distribution networks. in J Water SRT Aqua, **45**(5), pp. 221-231.
9. Herz, R.K. 1998, ‘Exploring rehabilitation needs and strategies for water distribution networks’, in J Water SRT Aqua, **47**(6), pp. 275-283.
10. Herz, R.K. and Hruza, P. 1997, ‘Rehabilitation needs of the Vienna water supply network’, in Water Saving Strategies in Urban Renewal: European Approaches, pp. 105-124, European Academy for the Urban Environment, Dietrich Reimer, Berlin.
11. KANEW in: www.tu-dresden.de/biwiss/stadtbau/KANEW.html
12. Kleiner, Y. and Rajani, B.B. 1999, ‘Using limited data to assess future pipe replacement needs’, in J AWWA, **91**(7), pp. 47-61.
13. Müller, N. 1998, Kosten - Nutzen -Untersuchung vorbeugender Rohrnetzerneuerung, dargestellt am Beispiel des Wasserrohrnetzes der Stadtwerke Chemnitz (Cost-benefit analysis of preventive pipeline rehabilitation, case of water network of City of Chemnitz), Diplomarbeit (Master Thesis), Lehrstuhl Stadtbauwesen, TU Dresden.
14. Nessie Model in: www.nessiemodel.com
15. Rajani, B.B. and Kleiner, Y. 2001, ‘WARP - Water Mains Renewal Planner’, Paper presented at International Conference on Underground Infrastructure Research, Waterloo, Canada.
16. Saegrov, S., Melo Baptista, J.F., Conroy, P., Herz, R.K., LeGauffre, P., Moss, G., Oddewald, J.E., Rajani, B.B. and Schiatti, M. 1999, ‘Rehabilitation of water networks - survey of research needs and on-going efforts’, in J Urban Water, **1**(1), pp. 15-22.