Whole of Life Cost Calculations for Water Supply Pipes

D. Fuchs-Hanusch*, B. Kornberger**, F. Friedl*, R. Scheucher*

* Institute of Urban Water Management, Graz University of Technology, Stremayrgasse 10/I, 80 10 Graz, Austria
** Institute of Statistical Applications, Joanneum Research, Steyrergasse 25, 8010 Graz, Austria

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INTRODUCTION

Selecting proper pipes at the right time for rehabilitation is one of the main challenges in asset management. As water supply pipes have a long lifetime in which they have to be operated and maintained, the replacement decisions should focus on long term cost calculations. The costs associated with aging pipes are mainly related to pipe breaks and maintenance work as well as water losses. As the factors that influence break occurrence and pipe maintenance, repair and water loss costs are manifold; there are two challenges of lifetime costs calculations. One is to predict future breaks of pipe units. The other is to estimate how costs differ from pipe to pipe and how they will alter with time.

Pipe failure prediction models can be classified into physical and statistical models. Physical models (e.g. Rajani, at al 1996) require detailed data about the surrounding situation and the internal and external loads that affect the pipes. The collection of such data causes high costs. This data collection seems to be justifiable only for pipes with a high vulnerability and a high risk to cause external damage, like it can be expected for transmission mains. Therefore, to calculate future breaks in the entire supply systems statistical models are preferred. Kleiner and Rajani, 2001 gave a review of statistical models for predicting pipe breaks proposed in the scientific literature. The statistical models described in Kleiner and Rajani, 2001 are classified into deterministic, probabilistic single-variate and probabilistic multi-variate models. Deterministic and probabilistic single-variate models are particularly usable to determine the breakage rates for pipe groupings (same material, same vintage, same soil-type). To calculate whole of life costs for individual pipes, failure prediction at the pipe level is essential. Therefore in our research a probabilistic multivariate model, the proportional hazards model (Cox, 1972) was adapted. For the purpose of pipe failure prediction the proportional hazard model (PHM) was first used by Marks et al., 1985 and further amended by Andreou et al., 1987 and Le Gat and Eisenbeis, 2000. The purpose of these models mainly was to calculate the yearly number of failure accurately. In our analysis a PHM was adapted to fulfill the requirements for whole of life cost calculations. These requirements can be described as follows. Inflation and changes in construction prices costs alter with time on a yearly basis. Therefore the focus in our analysis was to estimate the years when the failures occur with a defined probability, rather than to estimate the cumulated number of failure over time.

Estimating the costs of aging pipes due to maintenance and failure is the second challenge in whole of life cost calculations. Kleiner, et al 2010 describe a life cycle cost equation for supply pipes which involves rehabilitation costs, failure costs including repair costs, external direct costs and costs for water losses due to failure as well as indirect external costs and social costs. Kleiner at al., 2010 neglected costs of maintenance, like inspection and smaller repair works and leak detection which increase with the deterioration of pipes as well. Further the prize increases and inflation rates were neglected as well. In this paper we describe an amended equation of the one given in Kleiner at al., 2010 where these additional cost factors have been taken into account. The sensitivity of these factors on the results of the optimal time of rehabilitation was investigated. Therefore influencing factors on the variance of repair costs including external damage and water loss costs were investigated by analyzing cost data of three

Austrian water utilities. These utilities were participating in the research project IRM – “Infrastructure Rehabilitation Management”, part of the KNet “Waterpool”, a competence network between Austrian research institutions and the water economy, funded by the Austrian Ministry of Economy, Family and Youth.

The entire paper is structured the following. Section 1 describes the whole of life costs approach for supply pipes used in the research and gives results of the sensitivity analysis. Section 2 shows how the data of three Austrian utilities have been used and structured to provide optimal segments for modeling whole of life costs and for failure prediction. Further this section describes how a PHM was used and amended to fit to the requirements of WLC and pipe rehabilitation prioritization. Finally conclusions and an outlook about WLC calculations are given.

WHOLE OF LIFE COST (WLC) CALCULATIONS FOR WATER SUPPLY PIPES

Definition of WLC functions

The costs of a deteriorating pipe (i) over time (t) are mainly caused by pipe failure (PF) and include direct and indirect costs. Direct costs are costs for pipe repair (C^{REP}) as well as external costs (C^{EXT}) due to external damage like street body reconstruction and costs for water losses per leak or break (C^{PFWL}). Mentioned in Kleiner et al., 2010 indirect costs include social costs (disruption, time loss or loss of business) and indirect external costs (sewer damage, accelerated street deterioration). These costs were neglected in our investigations, because to estimate them on a monetarily basis is an additional and complex topic. Therefore we concentrated on the direct costs. But in addition to Kleiner at al., 2010 further direct costs have been taken into account like inspection and maintenance costs ($C^{I\&M}$). These costs rise with the age of a pipe as well, as aging pipes have higher reparation needs of valves and hydrants as well as a higher necessity of water loss detection campaigns. Further higher water losses due to higher background leakage (C^{BL}) may occur at deteriorating pipes. Finally, at a specific time in the life cycle, the pipe has to be rehabilitated (C^{Reha}). Then the life cycle starts again for the new pipe.

$$(1)\quad C^{tot.}_{(i,t)} = C^{REHA}_{i,t} \cdot e^{-z_1.t} + C^{oldPipe}_{i,t}$$

$$(2)\quad C^{oldPipe}_{i,t} = \sum_{j=1}^{t} \left(PF_{i,j} \cdot \left[\left(C_i^{REP} + C_i^{EXT} \right) * e^{-z_1.j} + (C_i^{PFWL}) \cdot e^{-z_2.j} \right] + (C_i^{I\&M} e^{a_i.t} + C_i^{BL} e^{b_i.t}) \cdot e^{-z_2.t}) \right)$$

To calculate these costs over time, equation (1) and (2) were formulated. The aim is to derive the optimal time of rehabilitation (t_{opt}). It is reached when C^{tot} becomes a minimum. In distinction to Kleiner et al., 2010 we included the influence of future price increases into the discount indices. Therefore the index z_1 considers the discount rate minus building cost index and z_2 considers the discount rate minus consumer price index. For all costs which refer to the construction sector (C^{Reha}, C^{Rep}, C^{EXT}) z_1 is taken into account, for all costs which are influenced by inflation, z_2 was used. For the increase of background losses (BL) and inspection and maintenance work (I&M) with time, the factors a_i and b_i have to be estimated.

The factors, that influence the specific costs as well as the failure rates and hence the WLC, vary strongly from pipe to pipe. Data acquisition to derive specific costs per pipe unit for the entire supply system can be a time extensive work. For a better understanding of the main influencing factors on the result of $t_{opt,}$ a comprehensive sensitivity analysis has been started, using a Monte-Carlo-simulation and the method of Morris. For this analysis the open source software SIMLAB (2011) was used.

It is obvious that the amount of expected failure in the near future is a main influencing factor on the result for t_{opt}. Chapter 2 deals with this topic separately and describes the derived failure model, uncertainties and verifications of the model in detail. In a first sensitivity analysis, we assumed that the number of future failure is given. An extended sensitivity analysis (SA) incorporating the SIMLAB SA Methods, the external failure prediction model and the WLC calculation model is still in progress. So far failure and rehabilitation cost related factors and factors related to water losses and maintenance work intensity have been taken into account by analyzing equation (1) and (2) for a fixed future failure rate.

The parameter range of these factors were derived from data and expert information of 3 Austrian water utilities, data provided by Statistic Austria (www.statistik.at) for the prize indices and data from the official report of the Austrian Benchmarking Project (Neunteufel et al., 2008). From this report the water prize range in Austria was derived. For the factors related to water losses, results of Lambert, 2009 were taken into account.

Value Ranges of WLC Factors for the Monte Carlo Simulations

Figure 1 shows cost variations for direct failure repair costs. The main influencing factor on costs is the road type, due to different pavement structures. As material cost variations per diameter are low the influence of pipe diameter is low as well and can be neglected when pipe specific repair costs are derived. The repair type has a slight influence on the costs as well. The data analysis of the participating water utilities has shown that the repair types mainly result from pipe type. For example PVC pipes, due to longitudinal cracks have to be partially renewed, while most cast iron pipe breaks are round cracks and can be repaired with repair saddles. Due to these results we recommend in any case to include data acquisition about road type and frequent pipe crack types if a pipe individual WLC cost calculation is planned. The influences on rehabilitation costs were investigated on the basis of rehabilitation cost of the utilities (Figure 2). The costs were accumulated to the present. The analysis has shown that an influence of diameter is given in this case. Figure 2 shows that the cost vary significantly and that the distribution type depends on the diameter. While for diameters up to 100mm the values follow a normal distribution, for the bigger diameter the distribution tends to be left skrewed.

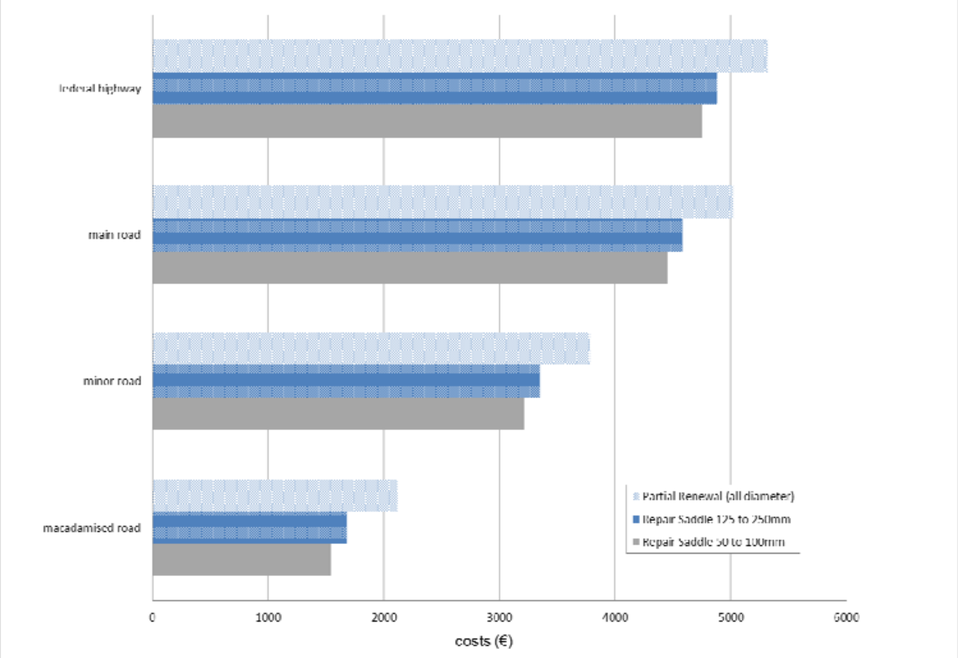

Figure 1: Direct failure cost variations due to repair type, road type and diameter (Data source: 2 Austrian utilities)

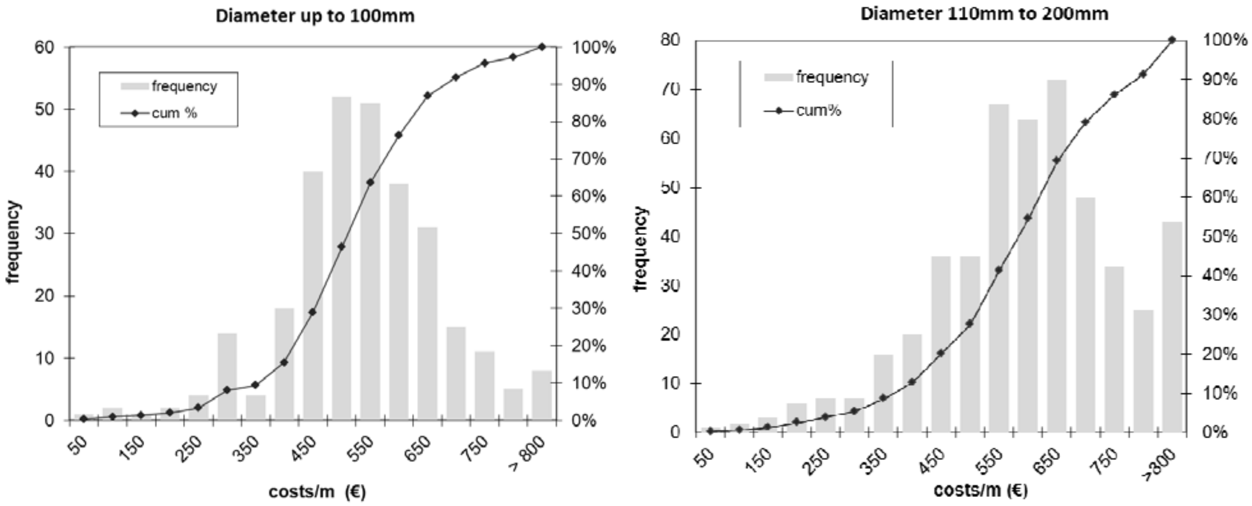

Figure 2: Rehabilitation costs/m for pipes 100mm and 110mm to 200mm (Data source: 1 water utility)

For quantifying the range of water losses due to pipe failure (PFWL) and background leakage (BL) estimations of Lambert, 2009 were taken into account. Physically C^{PFWL} depend on the type of failure, the diameter of the pipe or the extent of the leak and on pressure. Lambert, 2009 gives a range for losses per pipe failure for an average pressure of 50m. He classifies the losses per failure in losses from reported leaks and breaks with short runtime and losses from unreported leaks and breaks with longer runtime (see also Figure 3). Further he provides an empirical function to calculate background leakage in dependency of water main length (LM) average zonal pressure (AZNP) and the number of service connection (SC/km) per water main length (Equation 3).

(3) $BL\ (\text{litres/hour}) = (20xLM + 1.25xSC)*(AZNP/50)^{1,5}$

The amount of the pipe individual background leakage depends on the type/vintage of pipe joint and on the amount and the age of the connected supply pipes. Equation (2) assumes an exponential increase of this background leakage with time. The hypothesis of an increase of background losses is physically constituted in the hypothesis that the amount of leaking joints and house connections increase with time. These types of leaks are not detectable because the leakage itself is small but the amount of such leakages increase. To verify this hypothesis an extended literature research and an expert’s opinion poll according to background losses has been started. So far the factor bi of equation (1) was varied between 0,5% and 3% increase of background losses per year due to experts estimations.

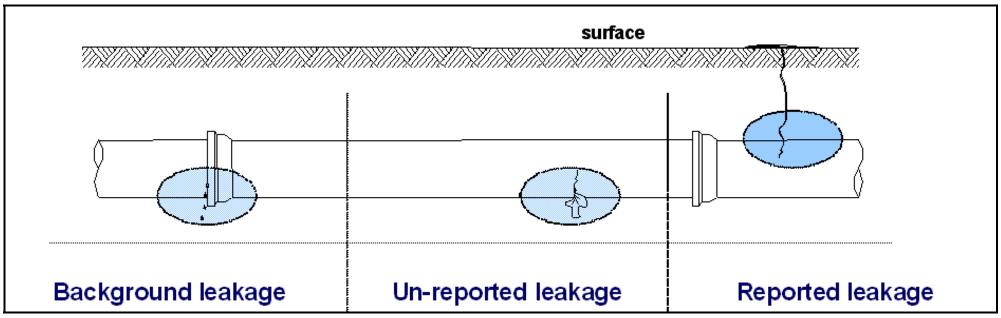

Figure 3: BABE (Background and Bursts Estimates) concept for types of leakage (Lambert, 2009)

According to the expected inspection and maintenance costs the range was defined by expert opinion as well. It was set between 0,5 and 1,5 €/m pipe and includes leak detection, valves and hydrants inspection and small maintenance works. Table one gives an overview of the defined value ranges for the parameters used in equation (1) and (2) for WLC calculations.

Table 1: Value range for relevant factors of equation (1) and (2) to investigate the sensitivity at an average pressure of 50m, a fixed failure rate for pipes with a diameter up to 100mm and an average length of 200m

	min	**max**	**distribution**	**data source**
C^{Reha}	250 €/m	750 €/m	normal	utilities data
$C^{Rep}+C^{ext}$	2.500 €	6.000 €	normal	utilities data
z_1	0	0,02	uniform	Statistic Austria
z_2	0,02	0,05	uniform	Statistic Austria
WP	0,7 €/m³	1,6 €/m³	beta(α,β=2;a=0.7;b=1.6)	OEVGW Benchmarking
WLperB	300 m³	7000 m³	uniform	Lambert, 2009
BL mains	0,02 m³/km/h	0,04 m³/km/h	uniform	amended from Lambert, 2009
BL per SC	0,001m³/SC/h	0,003m³/SC/h	uniform	amended from Lambert, 2010
SC/km	10	60	uniform	OEVGW Benchmarking
bi	0,005/a	0,01/a	uniform	utility experts
$C^{I\&M}$	0,5 €/m	1,5 €/m	uniform	utility experts, utilities data
ai	0,005/a	0,01/a	uniform	utility experts

Sensitivity Analysis - Morris Screening Method

A sensitivity analysis using the Morris screening method provides the opportunity to define factors that influence the result, as well as factors which have a high dependency to other factors and to input data. If C_{tot} is analyzed with a Monte Carlo Sample for the cumulated costs of aging pipes $C^{oldPipe}$ plus rehabilitation costs C^{Reha} the significance of C^{Reha} and z_1 is dominant. Hence a detailed investigation of expected rehabilitation costs for different pipe units is essential for WLC calculations. As we wanted to identify the cost driving factors more detailed, the sensitivity of costs factors with impact on $C^{oldPipe}$ (Equation 2) were of interest as well. In Table 1 all factors related to $C^{oldPipe}$ are marked with grey background.

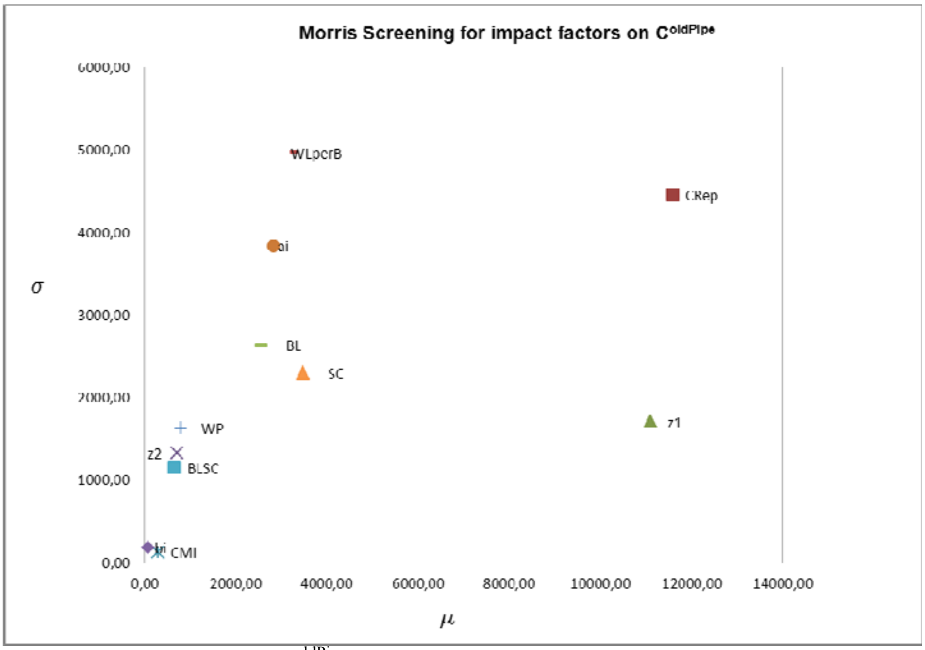

Figure 4: Sensitivity of $C^{oldPipe}$ on the parameters given in Table 1 for fixed break intensity and pipe length for pipes with diameters up to 100mm under an average pressure of 50m

Figure 4 shows the result of the Morris screening of $C^{oldPipe}$. Factors with high μ-values reflect a high impact on the result of $C^{oldPipe}$. High σ-values reflect a high dependency on other factors of the equation or on the input data, which are pressure, pipe length and the amount of failure. For example CMI and bi have no dependency on other parameters and are generally of low influence on the calculations. The analysis shows that repair costs (C^{Rep}) over time and the factor z_l have the strongest influence on the costs of the aging pipe if future pipe failures are given. Further the calculations of $C^{oldPipe}$ are sensitive on the amount of water losses per break (PFWL) and the number of service connections (SC) and the background leakage per m pipe length (BL).

The sensitivity analysis has shown that for a detailed data acquisition per pipe unit, with the aim to prioritize them for rehabilitation on basis of a WLC calculation, information about expected rehabilitation and repair costs and the expected price index z_l are of the highest interest. The water losses per failure (PFWL) as well as background losses in their amount but not how they increase in future (b_i) are of further interest as well. According to maintenance and inspection costs the variations in the specific costs CMI are of no significance, but if and how they increase with deterioration (a_i).

Calculating Ctot for an example pipe (fixed failure rate, 100mm diameter and 250m length) using the average value of Table 1 for each of the factors of equation (1) and (2) provides 15years to reach t_{opt} as result if only C^{rep}+ C^{ext} and C^{reha} are taken into account. 10 years are left to reach t^{opt} if costs for PFWL are incorporated as well and only 3 years to reach t_{opt} if costs for BL and I&M are incorporated as well. If a reduction of rehabilitation costs can be achieved, for example due to coordinated construction sites, t_{opt} is reached at present because the rehabilitation costs currently are less than at any time in the future.

Two of the main WLC influencing cost factors C^{Rep} and PFWL depend on the amount of future failure and the time of occurrence of failure. So far the failure rate was presumed as given for the sensitivity analysis. The following chapter describes a failure prediction model which was adapted to fulfill the needs of WLC calculations. Further the constraints of failure prediction are shown.

PIPE FAILURE PREDICTION AND REHABILITATION PRIORITIZATION WITH WLC CALCULATIONS

Pipe failure prediction models in context with pipe rehabilitation prioritization have the purpose to estimate the amount and the time of occurrence of future failure. The purpose of modeling the amount of future failure is to describe how the entire system reacts on rehabilitation of specific pipes. Estimations of the time of failure occurrence on the pipe level are of interest if prioritization itself is the target. Both targets have been taken into account within the described research.

Data preparation

To analyze failure data on the pipe level and to calculate the optimal time of pipe replacement the use of GIS data is common practice. As there are no standards, and the aims of the GIS can differ from utility to utility the data basis and the data structure vary widely. The pipe data of the participating Austrian Utilities were structured into very small units, as they were divided by each house connection. Further many of the older segments were divided by smaller younger segments due to past partial replacements. Therefore the data were restructured to fit to the needs of failure prediction and WLC calculations. On the one hand the segments should be representative units for the deterioration processes and on the other hand the segments should be convenient units for rehabilitation. The aim was to have pipe segments which represent the current state of deterioration, especially due to the number of previous failure (NOPF) and segments with an average length of 200m, which represents the average rehabilitation length in the investigated systems. Several rules have been defined to derive these applicable pipe segments.

Figure 5 shows a scheme of the restructuring process, which has two steps. The first step is to generalise the pipes to bigger units and the second is to split them into representative segments again. The main rules for generalisation were to unite pipes with the same material, vintage (± 5 years) and the same diameter and to ignore small parts in between which are not longer than a specific length. For the splitting process a maximum and minimum pipe length was defined. Further a maximum distance between failures was set. The documented failures are finally relinked to the new pipe segment.

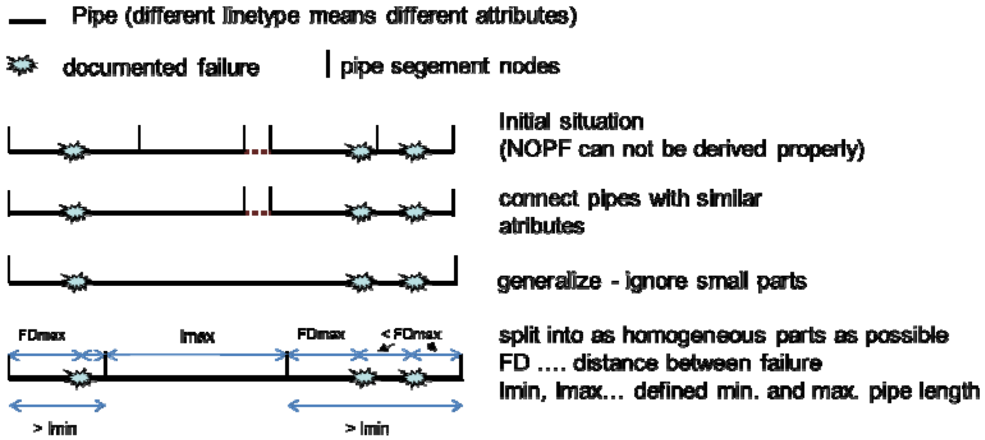

Figure 5: Restructuring of GIS data to define representative pipe segments for failure prediction and rehabilitation prioritization

For each new pipe segment the number of previous failure and the year of the last failure were added. Further the amount of service connections per pipe unit were added as an additional attribute. This new data structure provides an optimised basis for rehabilitation prioritisation and failure prediction.

Failure Prediction with PHM

The Proportional Hazards Model (PHM) (Cox, 1972) was designed to calculate the hazard rate h(t) of units (i). The hazard rate describes the probability of a unit i at a time t to fail in the next time step (t+1). The survival function of a unit S(t,i) can be derived from the hazard rate. By calculating S(t,i) the probability for the units to survive a specific time is given (Figure 7). Hence the time of occurrence and the amount of failures for a calculation period can be estimated with a certain probability.

To analyse the main influencing factors on failure occurrence in the participating systems a cox regression analysis was undertaken. The covariates which were investigated were material, diameter, length, vintage, soil type and the number of previous failure. One aim was to derive a general model to be used for individual pipe systems failure prediction by end users of the software PiReM Systems (Fuchs-Hanusch et al., 2008). This software was developed within a previous research project of the competence network KNet “Waterpool”.

As shown in Figure 6 and in previous research (Le Gat & Eisenbeis, 2000; Rostum, 2000; Park & Longanathan, 2002; Gangl et al., 2009 amongst others) the number of previous failure (NOPF) is of high significance in failure prediction. For the failure data of the participating Austrian supply networks the significant covariates were found to be NOPF as well and additionally material, diameter, vintage and length. We decided not to include the NOPF as a covariate of the model directly. Instead we build an own model for each time to failure (installation to first, first to second, second to third,…). This allows to incorporate right censored data of each survival to failure time properly into the estimations. Right censored data in this case are pipes which still wait for the next event. If this fact is neglected for parameter estimations the model tends to overestimate the failure probability.

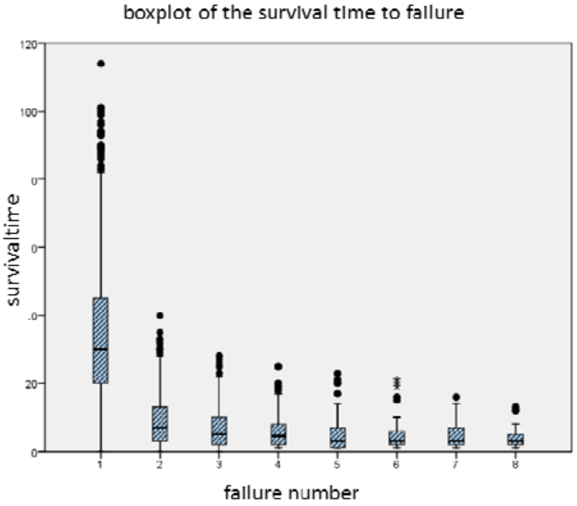

Figure 6: Survival time dependency on NOPF for the supply networks of 3 Austrian utilities.

Equation (2) describes the survival function S(t,i) for the first failure considering the influencing factors material (mat) as categorical covariate and the diameter (dia), pipe length (len) and the Vintage (vin) of a pipe as numeric covariates. These covariates were found to be significant for all 3 example supply systems.

$$(2)\quad S(t,i) = [S_0(t)]^{\exp(x_{mat}'\beta_{mat} x_{dia}'\beta_{dia} + x_{len}'\beta_{len} + x_{vin}'\beta_{vin})}$$

The survival function S_0(t) and the parameter β_{mat}, $\beta_{dia,}$ β_{len} and β_{vin} vary between the supply systems. Further the significant covariates for the failure models of the second and further failures may differ from the first failure model. Table 1 shows the estimated parameters for an Austrian supply network. The number of significant covariates decreases with the number of failure. The statistical significance of the model covariates was tested with WALD test and log-likelihood ratio using the software PASW Statistic 18 (2009). The bigger the Wald values of a covariate in Table 1 the higher the significance. The covariates of low significance are excluded in a next model estimation step. The remaining parameters are estimated anew.

Table 2: Significant covariates and parameters β_i for several survival time models of one Austrian supply network

	1st failure		**2nd failure**		**3rd failure**		**4th failure**		**6th failure**	
events (#)	871		457		262		158		98	
censored (#)	4750		370		169		91		56	
missing values	0		44		26		13		4	
Covariates	β	Wald	β	Wald	β	Wald	β	Wald	β	Wald
DN	-0,004	41,886	-0,004	11,399	-0,005	11,049	-0,006	6,109	-	4,371
MAT_Cat		264,811		16,95		6,623		8,499	-	4,74
AC	0,406	2,745	-1,063	4,215	-	-	1,006	,624	-	-
CI_LJ	0,564	18,018	-0,146	0,304	-	-	,421	,277	-	-
CI_SJ	0,928	91,795	0,058	0,048	-	-	,651	,258	-	-
all others	-2,096	60,721	-0,51	0,987	-	-	-	-	-	-
St	0,479	5,783	-	-	-	-	-10,466	165,137	-	-
DI_NCP			-2,66	0,95	-	-	-	-	-	-
DI_TC	-1,622	74,29	-0,984	4,566	-	-	-	-	-	-
Length	0,002	196,33	0,001	29,859	0,001	21,852	0,001	9,549	-	4,678
Vintage	0,042	179,625	-	4,29	-	2,189	-	1,872	-	0,99

The investigations have further shown that PVC pipes tend to have higher failure rates at bigger diameters but for all other materials the failure rate decreases with the diameter (negative β_{dia}). Therefore it is advisable to build a separate failure model for PVC pipes or include a combined variable Material times Diameter. For the implementation of the failure model into the software PiReM Systems we decided to group the pipes before estimating the remaining parameter βi, which then are $\beta_{dia,}$ β_{vin} and β_{len}.

As recognizable in Figure 6 and Figure 7 the steepness of the survival function increases with the amount of previous failure. Hence the insecurity in failure occurrence prediction decreases with the number of previous failure. For pipe rehabilitation prioritization it was found out in previous research (Gangl et al., 2009) that only pipes with more than 4 failures are of interest. This allows to assume that for pipes relevant for WLC calculations the insecurities in failure prediction can be minimized if previous failure data are recorded. Nevertheless for a better understanding of the insecurity in failure prediction regarding the sensitivity of WLC calculations further analysis is in progress.

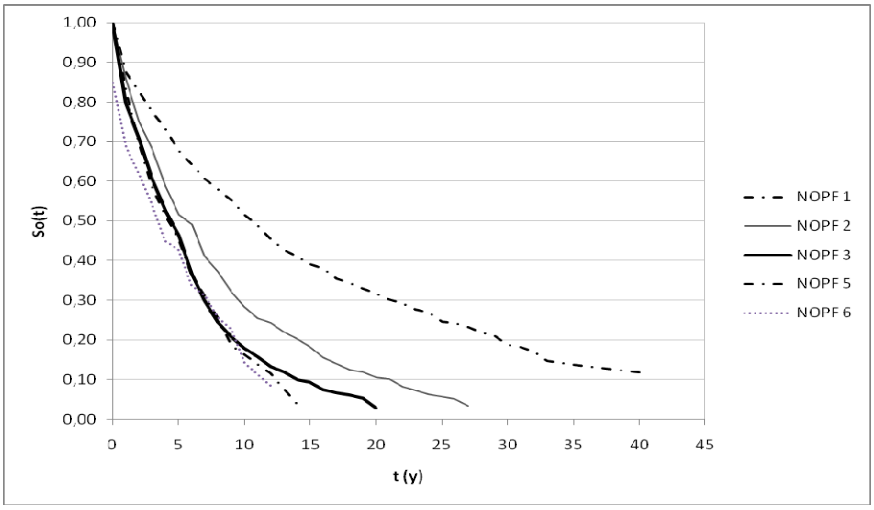

Figure 7 Survival probability baseline hazard for different numbers of previous failure (NOPF)

Finally, to validate the accuracy of the model, the number of predicted failures over time, was compared with the observed failures. Therefore the pipe data were structured as described above and for each pipe the time to failure occurrence (median value) was calculated for a defined time period. The validation for a partial network of one participating utility is shown in Figure 8. The satisfying adjustment is assumed to be a result that the break data of the example network reach back to 1974.

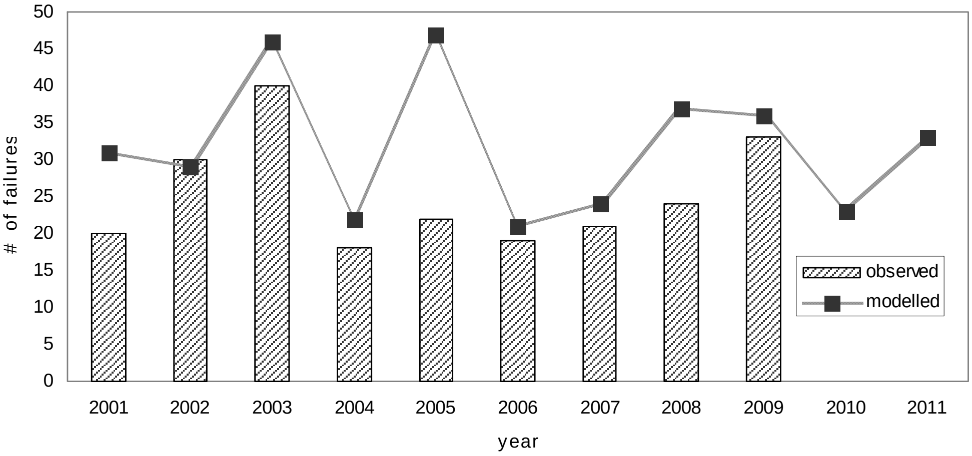

Figure 8: Model validation for a partial network of a participating utility

The accurate calculation of the cumulated future breaks, like it is shown in Figure 8 is the basis for calculating the effects of rehabilitation priority decisions on the future amount of failures (Figure 9) and on future failure costs. PiReM Systems (Fuchs-Hanusch et al., 2008) provides a module to define scenarios for yearly rehabilitation amounts. Figure 8 shows future failure trends for a defined scenario under rehabilitation of pipes prioritized with cost calculations.

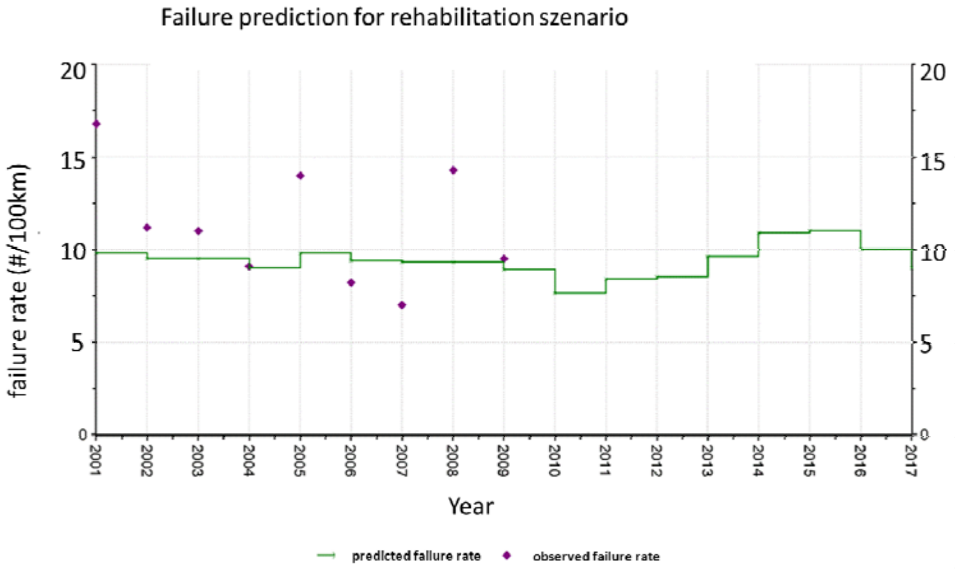

Figure 9: Failure prediction for a rehabilitation scenario in an example network (PiReM Systems)

CONCLUSION AND OUTLOOK

The times when future failures occur are undoubtedly of main interest in decision support for prioritizing water mains for rehabilitation and hence are an essential part of WLC calculations. For failure time prediction of individual pipes statistical methods are preferred to physical models, as failure data collection has started to be common practice at water utilities but the exact physical circumstances of breaks are hardly known. The described adapted PHM allows to predict the time when failures occur with a certain probability. The insecurities in failure time prediction decrease with the NOPF, hence for pipes which are of relevance for WLC oriented prioritization the insecurity in failure prediction decreases. Nevertheless for minimizing these insecurities in failure prediction an extensive pipe oriented failure statistics is essential. We assume that this statistic may include only a few describing factors, like pipe length, material, diameter, vintage and the time of occurrence but pipes with frequent failure have to be identified properly. It is advisable to structure the data basis into pipe units, which can be expected to be homogeneous due to their deterioration. The failure statistics may also be a short time series but enough of the pipe units should have achieved a certain amount of failure so far. An extended sensitivity analysis (SA) incorporating the SIMLAB SA Methods, the failure prediction model and the WLC model is still in progress. This analysis will provide more conclusions about the impact of uncertainties in failure prediction on WLC calculations and hence rehabilitation prioritization.

Assuming the future failure as given, the sensitivity of the WLC function on the variability of the remaining factors on lifetime costs have been analyzed so far. The main influencing factors on WLC were found to be the rehabilitation costs (C^{reha}), the repair costs including external costs (C^{rep} + C^{ext}) and the prize index z_1. These factors are followed by the water losses per break (PFWL) and the amount of background losses (BL, SC) as well as the expected increase in inspection and maintenance intensities for aging pipes (ai).

Therefore a pipe unit oriented allocation of expected rehabilitation costs should be a central part of WLC calculations. The example data of the Austrian utilities have shown that the rehabilitation costs distribution depend on the diameter. While at small diameters the cost values are normally distributed, the variations of the costs for bigger diameters are left skewed. It can be expected that the variations themselves are caused by pavement structures, the number of service connections and the number of other pipes crossing. But this additional information could not be provided for the cost data used in the described analysis. Further according to C^{rep} and C^{ext} , information about the position of the pipe in the street body and the pavement structure is essential. Supplementary the expected failure types are of interest as they influence the repair type and hence the repair costs as well. Z_1 as an additional sensitive factor represents the discount rate minus the expected construction prize index, which in our case were derived from data provided by Statistic Austria. Finally, for a better estimation of pipe individual water losses further research on the extent of water losses per break with respect to pressure and failure type is of interest. Regarding background losses the amount of service connections as well as pressure and type of pipe joint is of relevance. While the number of service connections per pipe can be easily derived from GIS data, less is known about individual background leakage per pipe joint and service connection. Closing this information gap is of interest for future research as well. Finally the influencing factors on the increase of pipe individual inspection and maintenance intensities should be incorporated in further information gathering processes as well.

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