Maintenance Management – Risk- and Condition-oriented planning for Vienna’s Water Pipe Network

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Introduction

Keeping pipe damage rates and hence water loss low is a central task of drinking water utilities. A maintenance planning approach that adopts strategic objectives is the basis for a targeted deployment of future reinvestments in water distribution networks. Pipe networks are subject to a variety of influences that impact and change the condition of pipes and valves. These changes can be described by means of mathematical models. A key basis for describing the status of pipe networks by means of mathematical models stems from the detailed documentation of the system in question and its status, as shown by the geographic network information system (NIS).

The present article describes the steps implemented in recent years to ensure condition- and risk-oriented maintenance planning for Vienna’s water pipe network. Condition and risk assessments were carried out over several phases for parts of the network and for pipe sections as well as for the installations pertaining to them. Loss and damage forecasts were conducted for this purpose, which permitted deriving a procedure to establish rehabilitation priorities.

Rehabilitation planning – Principles

According to the guidelines ÖVGW W 100, ÖVGW W 104 and ÖVGW W 105 of the Austrian Association for Gas and Water, pipe- and damage-related data are essential for any condition assessment. The most relevant attributes of pipe data listed in the guidelines are location, material, nominal diameter, vintage and length of the pipe section. Further it is recommended to keep historical data, including the date of rehabilitation. This data is also essential for the calibration of survival time models.

The Vienna Waterworks operate a network of approx. 3,300 km length supplying around 102,000 house connections. Incidents of damage to mains, distribution and connection pipes and fittings are recorded since the 1970s. From 2005 up to the present a comprehensive Network Information System (NIS) is used to collect information about the water supply system, to geographically analyse these information’s, to provide an assistance platform and finally to assist planning processes. This NIS unambiguously allocates damage incidents including the date and type of the damage to the pipe sections affected. Annually, approx. 350 of these damages involve pipes while roughly 1,200 involve valves or service connections. For a risk-oriented planning, additional information relating to the consequences of a damage (which is significantly codetermined by the volume of water leakage) was evaluated by factoring in the related pipe and road repair costs.

In order to take into account water losses in rehabilitation planning, an assessment of water loss and underlying trends for specific areas by means of water loss indicators

(ÖVGW W 63, 2009; Fuchs-Hanusch, et al., 2009) is recommended, since curbing water losses is one objective of rehabilitation planning. For Vienna's supply network, to include water loss reduction targets into the rehabilitation planning process, pipe sections were assessed on the basis of their potential to cause leakage. According to experts experience this potential relates primarily to grey cast iron pipes with socket-and-spigot joints, where gasket corrosion causes losses, as well as to sections with older connection pipes where the probability rises that screws of the tapped assembly are broken. Nevertheless the main driver for prioritising pipes for rehabilitation in the introduced methodology is calculating the optimal time of replacement based on a failure prediction model (Fuchs-Hanusch, et al. 2011).

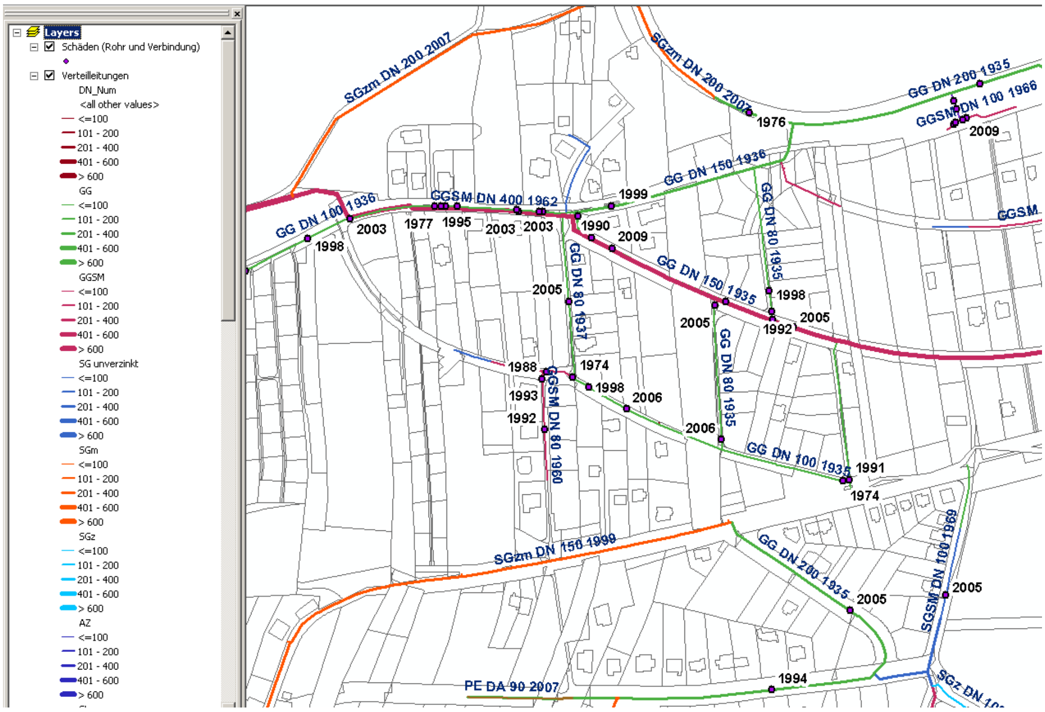


Figure 1: Pipe and damage database, NIS of Vienna Waterworks

Rehabilitation priorities – Methodology

The rehabilitation planning process for Vienna's water distribution system contains two steps. The first step is the long-time rehabilitation planning, where different rehabilitation scenarios are compared due to their effects on future failure rates and rehabilitation needs. The second step is the mid-term planning process which provides a pipe section classification for prioritisation. For predicting failure rates of the entire systems and compare them with values given in the Austrian standards of the ÖVGW W 100, both steps have to be combined in the simulations. In the first step, the pipe network was subdivided into groups characterised by varying levels of damage probability. On this basis, it was possible to define critical groups where increased water losses and damage costs may be expected in coming years. Critical groups whose damage incidents and leaks contribute significantly to water losses in Vienna include grey cast iron pipes with screwed sleeve joints (CISJ) and grey cast iron pipes (CI) with socket-and-spigot joints from the interwar period (GEN2: installed between 1921 and 1945) with nominal diameters of less than 250 mm, since these involve not only high damage probability but also long pipe sections. Since the late 1990s, the group of first-generation ductile cast pipes (SG, non-galvanised) with nominal diameters of up to 250 mm (500 km of network length) present an annual damage rate increase by approx. 10% and in 2009 attained 13S/100km. Figure 2 shows trends of the failure rates of these critical groups for the last 2 decades. A decrease in failure rates for the groups cast iron (CI) with screwed joint and CI with vintages after 1945 (CI < 250) results from rehabilitation programs concentrating not only on the oldest CI pipes but also on those with the highest failure amounts per pipe section.

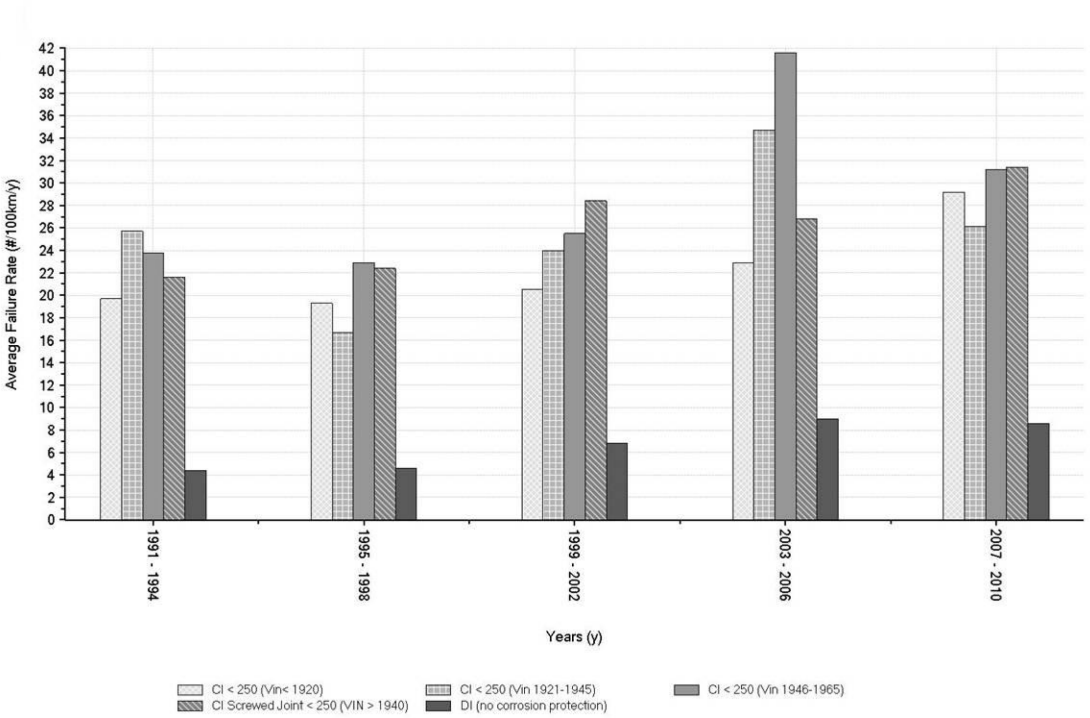
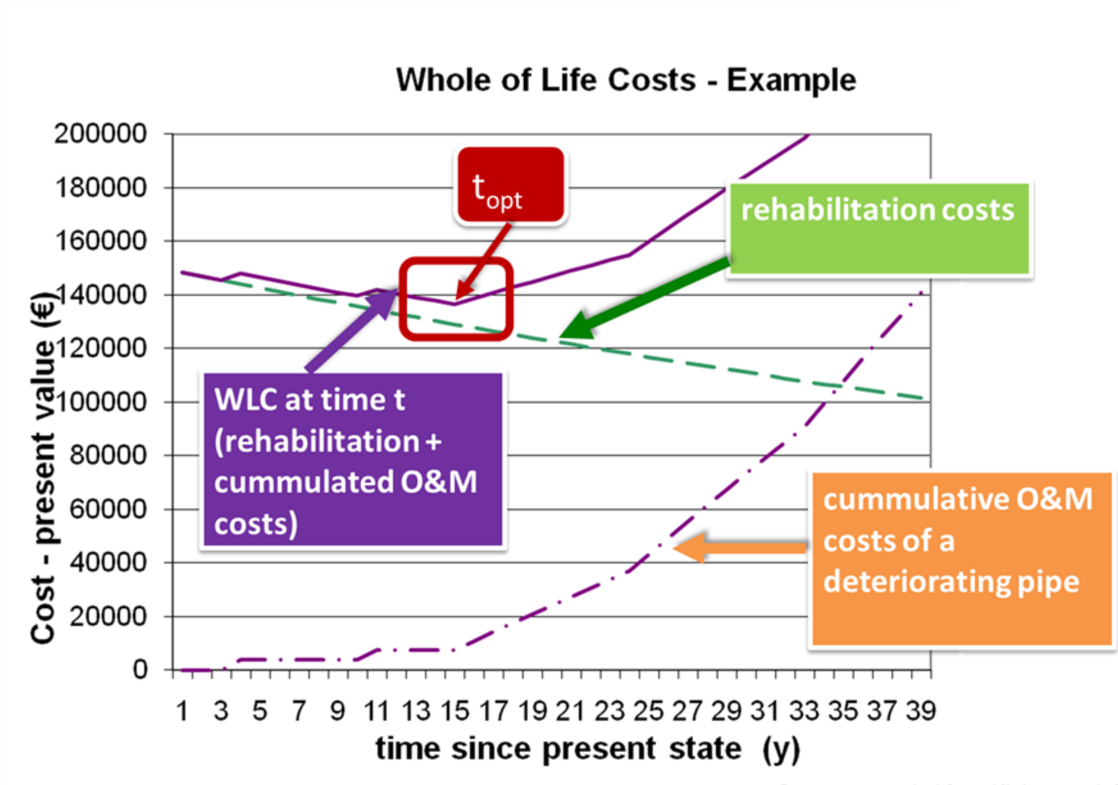


Figure 2: Significant pipe groups for rehabilitation

In order to define the mid-term replacement priorities, whole of life cost analyses were drawn upon to calculate the economically most feasible moment for replacement. This is equal to the moment when the aggregate costs of replacement and long-term maintenance of the old pipe are lowest.

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 the investigations for Vienna, as to estimate them on a monetarily basis would have required an additional and extensive study. Therefore the investigations concentrated on direct costs. The used whole of life cost (WLC) equations (equation 1 and equation 2) were amended from Kleiner at al., 2010.



Source: amended from Kleiner et al, 2010

Figure 3: The principle of WLC Calculations

In a first step a global sensitivity analysis was made to define the most relevant cost parameters. Therefore, besides the costs caused by pipe breaks, additional direct costs have been taken into account. Those were inspection and maintenance costs ($C^{I\&M}$) and increasing water losses due to undetected background leakage (C^{BL}). 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 and an increasing tendency to cause background leakage. Finally, at a specific time which can be optimised, pipe rehabilitation (C^{Reha}) has to be taken into account.

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

(2)

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

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} reaches a minimum. In distinction to Kleiner et al., 2010, Fuchs-Hanusch et al; 2011 further 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 were estimated as well.

A global sensitivity analysis using Monte Carlo Samples of the parameter space provides the opportunity to define factors that influence the results most. Hence this analysis was undertaken to define the factors for which a detailed data acquisition is required. If C^{tot} and t^{opt} is analyzed with Monte Carlo Samples the significance of C^{rep}, C^{Reha} and z_1 (depending on the discount rate and the construction prize index) is dominant. Hence a detailed investigation of expected rehabilitation and repair costs for different pipe units is essential for WLC calculations.

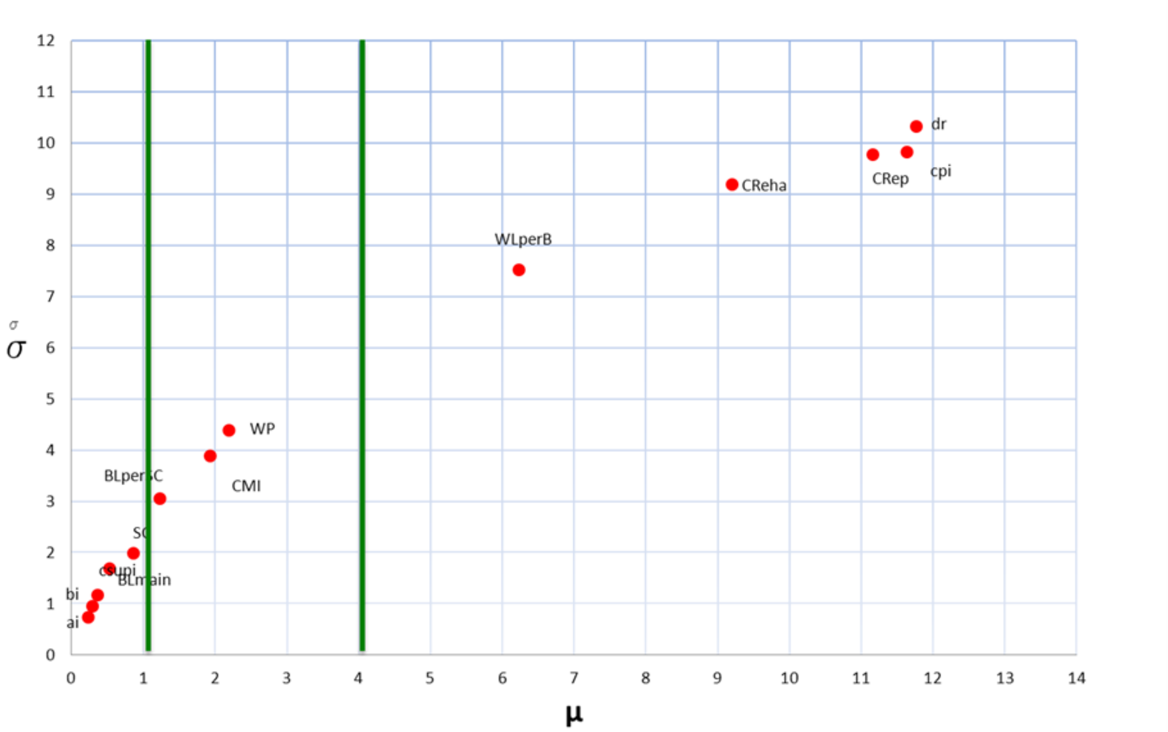


Figure 4: Sensitivity of topt on the parameter variations of cost relevant input data for a fixed break intensity and pipe length

Figure 4 shows the result of the Morris screening of topt. Factors with high μ-values reflect a high impact on the result. 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. The analysis shows that repair costs CReha, CRep and the prize indices discount rate (dr) and construction prize index (cpi) have the strongest influence on the result. Further the calculations of topt is sensitive on the amount of water losses per break (PFWL) the costs for Inspection and maintenance (CMI) and the costs for water (WP) have an influence as well.

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 indices are of the highest interest followed by the water losses per failure (PFWL).

Hence for Vienna’s Supply System the maintenance costs are calculated on the basis of extent of damage (assessed as monetary damage cost) and frequency of damage (by means of a probabilistic model). For predicting pipe failure a proportional hazards model (PHM) is used. For each number of failure (first, second, third,….) the significant parameters are derived separately. By knowing the number of previous failure on a pipe the time to the next failure can be predicted with a certain probability. The model building process is described in detail in Fuchs-Hanusch et al.; 2011.

Damage costs (costs of pipe and road repair) were determined subject to the respective types of repair work and road cover (Figure 5)

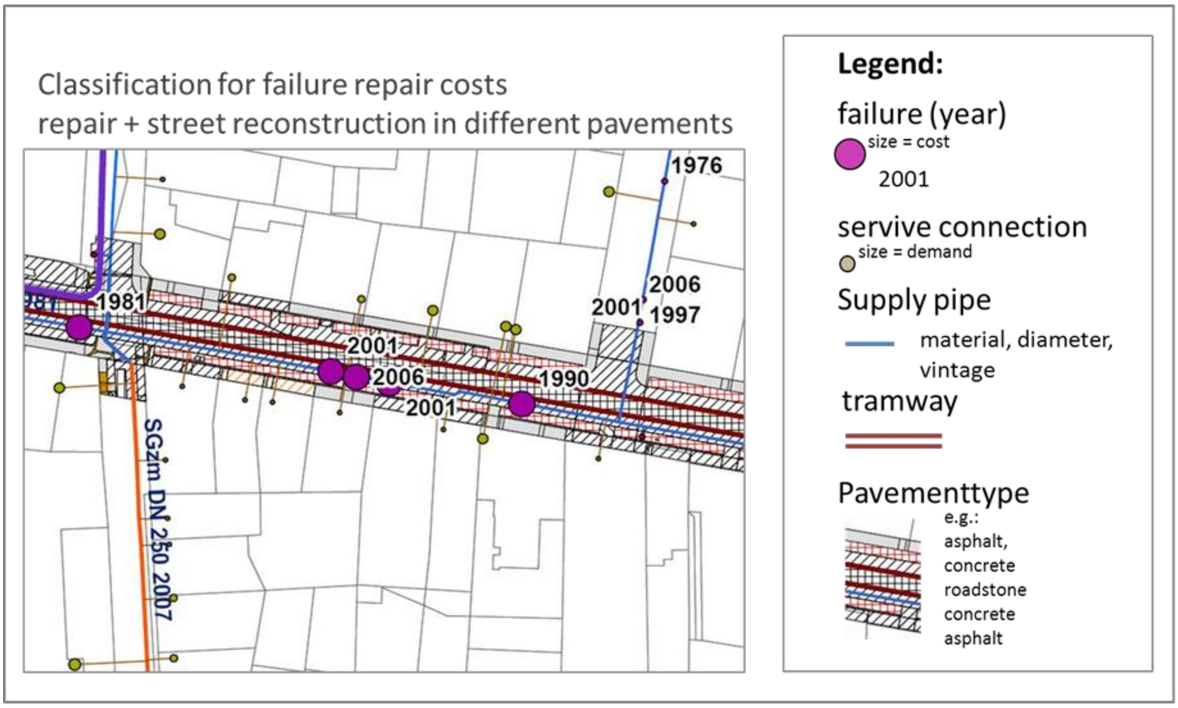


Figure 5: Detailed failure cost specification based on street and pavement type and repair type

The maintenance costs for each individual pipe are derived from the sum total of future expected damage incidents and conduit-specific costs of pipe and road repair as well as from the rising costs of maintenance (aging fittings) and inspection (leakages spotted more frequently). Water losses per break are not taken into account yet as the hydraulic modelling which is essential to estimate water losses at different pipe sections is still in progress.

Results

Life cycle cost calculations allowed for the determination of rehabilitation priorities for 35 km of pipes in Vienna. The sections involved include 17 km of CI (oldes grey cast iron), 12 km of CISJ (cast iron with screwed joints mainly used after world war II) and 5 km of DI (ductile iron of the first generation without corrosion protection); steel and asbestos cement account for the remainder.

As mentioned above, to integrate further risk-oriented assessment into this prioritisation, the pipes were subjected to an extended assessment of supply disruption risks by drawing on the consumption density coefficient ($m^3/km*y$) (Figure 6). In addition, the pipe sections were evaluated for potential risks of water loss by looking at the age of connection pipes and the materials used (Figure 6). This means from the 35km of economic priorities those are further prioritised which have a high risk of further leakage due to pipe joint type (CI with spigot joint) and old service connections as well as those with a high consumption density.

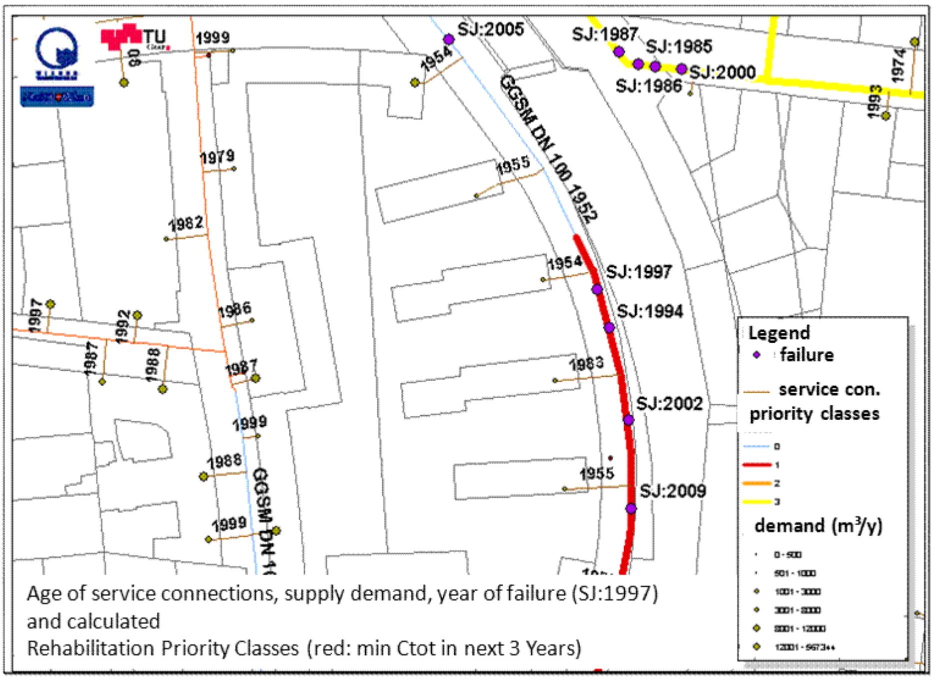


Figure 6 : Priority class (optimum moment for replacement), mean age of connection pipes and consumption density as key criteria of pipe replacement

In a final step, simulations where carried out where pipe sections were virtually rehabilitated by the means of PiReM Systems (Fuchs-Hanusch et al., 2008). PiReM Systems further provides a module to define scenarios for yearly rehabilitation amounts. These scenarios allow to define how much of the defined priorities are going to be rehabilitated on a yearly basis. This virtually rehabilitation of pipes of a defined yearly length is the basis for calculating the effects of rehabilitation decisions on the future amount of failures. Figure 7 shows future failure trends in Vienna’s supply system for a defined scenario length (15km/y) under rehabilitation of pipes prioritized in the way described above. An amount of 10 failures/100km/y in the entire system is the targeted long term failure rate. This failure rate is also defined in the Austrian standard ÖVGW W 100 as an achievable value.

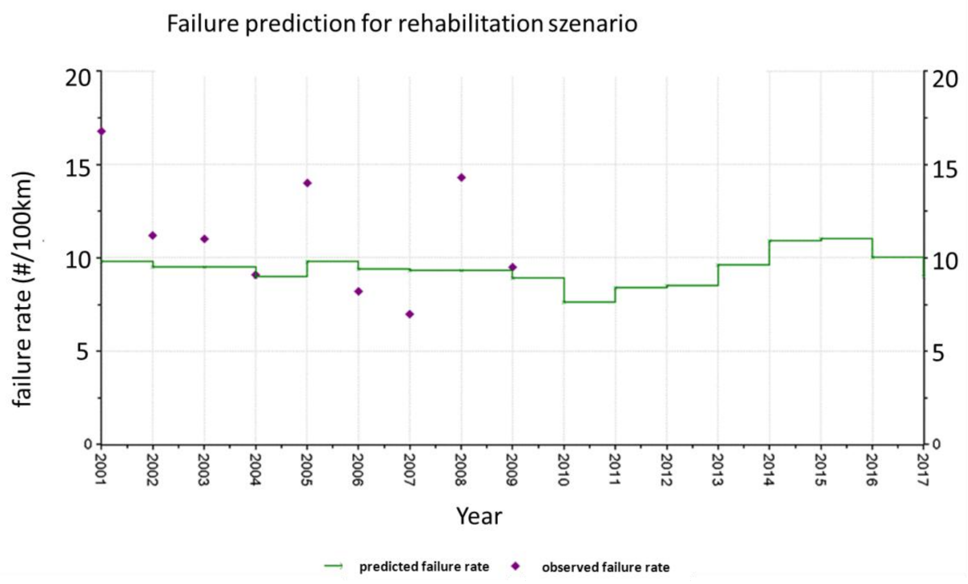


Figure 7: Failure prediction for a rehabilitation scenario of the Viennas Water Supply network (PiReM Systems)

Conclusions and Outlook

Long-term plans to bring water loss and damage rates in line with the reference values defined in Austrian guidelines can be implemented through the optimised distribution of rehabilitation works across critical pipeline groups. Risk- and condition-oriented planning allowed for formulating optimum reinvestment strategies that moreover take indirect account of potential water loss sources. Developing forecasts for modified replacement strategies helps to pinpoint potential effects on future damage incidents, and hence water loss, as well as the extent of future investment needs to improve the pipeline network status.

In the future, the decision-making process to identify pipe sections in need of rehabilitation should also take into account of water losses as those are relevant for results variation of t^{opt}. An application of pipe network hydraulics will support water loss estimations at the pipe level.

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