Analysis of the Long-term Effects of Maintenance Strategies

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**Summary**

The maintenance of water/gas distribution and sewer networks remains a permanent task due to the extent of necessary measures and the linked budget demands and therefore requires future-oriented strategies. The essential challenge of developing sustainable strategies consists in finding a way, which represents a long-term compromise between the requested service level and the costs. An important foundation for steering the development of costs (and within costs the issue of fees and tariffs) and the condition is the knowledge about the actual constructional state and the future aging of the network. Generally, pipe-based infrastructure networks are more or less subject to a continuous aging process. Here the aging pattern may vary clearly depending on the pipeline-specific characteristics, respectively the combination of characteristics (age, actual constructional state, DN etc.). Against the background, that the infrastructure networks extant today have been created in steps and in periods of different execution variations and laying qualities it can be assumed that the future demand for rehabilitation will strongly vary. A maintenance planning, in which the net-specific deterioration of condition occurring in the future is not realistically analyzed, inevitably leads to a misinterpretation of the demand for rehabilitation and financial means. In order to guarantee a long-term security in planning, it is therefore indispensable to analyze the characteristics of the local net aging and to include them on the scope of creating a strategy.

1 Introduction

The rehabilitation of drain and sewer systems is a continuous task due to the extent of the measures necessary and the financial means that have to be introduced. For
this reason it requires long-term and future-oriented strategies. The integral challenge in the development of strategies is to find a way which ensures the preservation of a network’s substance for the following generations within the conflict area of budget restrictions, fees and other requirements.

In the draft of the DWA-M 143-14 [1] various rehabilitation strategies are described and evaluated. But a net-specific analysis of the efficiency of a chosen strategy is only possible with the help of substantiated and reproducible strategy predictions. For that purpose substantiated statements concerning the future development of the network are particularly necessary besides a realistic evaluation of the constructional actual condition. This condition development can be determined from the network data at hand by taking a differentiated, deterministic aging model as a basis.

In general, infrastructure networks that are bound to lines are subject to a more or less continuous aging process. Here the aging scheme can vary in dependence on line-specific characteristics or/and their combination. This particularly applies for drain and sewer systems that have historically grown and are therefore very heterogeneous regarding their age, their constructional actual condition or the pipe material of the single sections, for example. A rehabilitation planning in which this situation and the future development of the network is not realistically included must inevitably lead to a miscalculation of the need for rehabilitation and investment. In order to ensure a long-term planning security it is indispensable to extensively analyse the characteristics of the local network aging and to include them in the strategy design.

A sound solution approach for this problem offers the comprehensible network management system "STATUS-Sewer"[2], which is introduced in the following.

2 Modelling of network aging with "STATUS-Sewer"

2.1 Plausibility check and section evaluation

Starting point of each qualified network analysis is an extensive analysis of the actual condition of the network or network part looked at. Here, it has to be considered that the significance of following predictions decisively depends on the completeness and consistency of the data taken as a basis as well as their analysis within the scope of the evaluation of the actual condition.

For this reason, previous to the start of the evaluation of the actual condition, the data is extensively checked by the plausibility check integrated in "STATUS-Sewer". Here not only the permissibility of the condition descriptions that are used is checked, but particularly the consistency of the inspection data against the background of the
available master- and condition data of the section looked at as well as of the 
neighbouring one. In addition, already available inspection reports of the particular 
section are included into the plausibility check in order to be able to identify 
implausible damage developments [3], [4].

The conventional systems for evaluating the condition predominantly orient at the 
ministerial "Arbeitshilfen Abwasser" (Working Aid Sewage) [5] or the data sheet ATV-
M 149 [6]. Here the condition class of a section, as a scale for the rehabilitation 
priority, is vitally determined by the damage class of the worst single damage and 
thus describes a locally limited section condition. From this classification can be 
derived how large the extent and spreading of the damage within the section is and 
resulting from that, how large the remaining reserve of wear is.

In order to achieve an evaluation which is as realistic as possible of the 
constructional section condition an advanced evaluation concept was integrated into 
"STATUS-Sewer", which divides the section evaluation into a condition class as a 
quantity of the present functional fulfilment (rehabilitation priority) and into a 
substance class as the quantity of the still inherent functional fulfilment (reserve of 
wear). Against the background that the substance class gives information about the 
still achievable remaining technical utility duration and the type and the extent of a 
necessary rehabilitation, the substance class is indispensable for assessing the 
aging behaviour [7].

By a specification of the damage classification which goes beyond the ATV-M 149 [6] 
by including relevant local limiting conditions like nominal pipe size, pipe material and 
laying depth, for example, an assessment of the inspection reports from an 
engineering point of view concerning their effects on stability, leak tightness and 
operation of the sections analysed is carried out [7]. As a consequence of the 
significantly more differentiated and more realistic evaluations, in this way the risk of 
wrong decisions within the scope of the rehabilitation planning is clearly reduced.

2.2 Aging functions as a foundation of the prediction

The aging process of drain and sewer systems depends on a variety of influencing 
factors and interdependencies similar to the lifetime of humans and cannot be 
grasped mathematically for a specific individual case. For the aging prediction the 
observed network aging of the past is mathematically represented instead and 
extrapolated into the future. For that purpose the cohort survival model, which was 
developed in demography, is applied [8]. In this case cohorts describe birth- or 
construction age groups that survive with decreasing probability the older they get.
According to that, the life time of a sewer is regarded as a statistic random variable to which a probability distribution can be related. In Figure 2 (left) a typical distribution of life time is illustrated with assimilation to the Weibull distribution.

It describes the probability by which a construction cohort reaches a certain age. The probability by which a construction cohort survives a certain age is described by the survival function (Figure 2, right). It is determined from the integral of the life time distribution. Since sewers are subject to continuous deterioration of the condition and since therefore a perspective that is limited to two conditions is insufficient (alive / dead), a modification of the aging model is necessary. For that purpose the survival functions are divided into classes analogous to the condition- and substance evaluation. So the result is particular sets of so-called condition- and substance survival functions.

The substance survival functions describe by which probability a construction year belongs to a certain substance class. The sequence of substance survival functions characterizes the relative period of pause of the sections in the substance classes and as a consequence gives information about the aging speed of the sections in relation to the substance in the network looked at. As far as the amount of data which is significant for a statistic analysis is available for different section characteristics, the substance survival functions can be created for section groups (e.g. vitrified clay or concrete sewers).

The substance survival functions, which are gauged for a drain and sewer network of a German major city, are presented in Figure 3 and Figure 4. By means of a cluster analysis, specific survival curves among other things were generated illustrating the different aging behaviour of these section groups:

- Concrete sewers DN<= 700
- Concrete sewers DN> 700
- Vitrified clay sewers
The set of curves is analysed by means of a vertical line which is subtended by the substance survival functions. The time-dependent probability vector of the single substance classes results from the partial lengths of the vertical line.

From the example of Figure 3 can be extracted that 30-year-old concrete sewers (DN<=700) in the network looked at are in the substance class "defect-free" with a probability of ca. 56 % on average, i.e. that they have the full or still a very high wear reserve. The probability of already belonging to one of the next worse substance classes is far lower.

The survival function in the no longer permissible substance area "breakdown" is of special importance. It shows the total reduction of the wear reserve and thus the end of the technical utility duration. Here the probability of a breakdown amounts to 6 %.

In comparison the vitrified clay sewers analysed in the example at hand are characterised by an aging that starts relatively early (Figure 4). According to the example, only an average of 8 % of the 30-year-old vitrified clay sewers possess the full wear reserve. Here probably the lower resistance to impact compared to concrete pipes and the danger of cracks connected to it when handling the pipes during transport and installation or when hardening the embedment makes an impact. The high defect proportion of cracks in the vitrified clay pipes confirms this fact. Nevertheless, in the following substance classes a consistent aging behaviour with relatively long periods of pause can be registered. On average, a probability of failure of 50 % exists only with the age of 68 years for the vitrified clay pipes in the network looked at.

Analogous to the calculation of substance survival functions, condition survival functions are determined in dependence on significant section characteristics.
The condition survival functions describe by which probability a construction year belongs to the single condition classes (Figure 5 and Figure 6).

### 2.2.1 Prediction of the network aging by Markov-processes

Whereas the survival functions illustrate the average aging behaviour of single characteristic groups which has been observed in the past, an extended analysis is necessary for the condition- and substance predictions of a network and single network elements.

Here the foundation of the substance- as well as the condition predictions is provided by the survival functions determined above as well as by the mathematical model of the time-discrete Markov chains. Markov chains allow to consider the condition- and substance development as a stochastic process over a longer period of time and thus to make predictions on future development [9], [10].

In the analysis of aging processes it is basically started from the assumption of unidirectional Markov chains. That means that the section condition and –substance can deteriorate without external intervention, i.e. that the condition- or substance development only runs into one direction. The aging process is completed if the worst condition- or substance class has been achieved and thus a failure occurs. This failure is temporary for the achievement of the last condition class since a repair enables the section to achieve a better condition class; whereas the achievement of the final substance class is definite for it can only be left by a renovation or renewal. But this way of intervention virtually completes the life time of the original section and motivates a new section entity.

By means of statistical analyses of inspection reports the different periods of pause in the particular condition- or substance classes are determined. Here the probabilities of a transition into the next worse condition- or substance class depend on the point in time and the age of the analysed section connected to it. This circumstance is expressed in the fact that for the transition from one condition- or substance class to
the next age-dependent, section- and network-specific survival probabilities are determined.

Figure 7 Markov-processes with transition probabilities $P$ between two conditions $(i;j)$

2.2.2 Section-related prediction

The accuracy of the prediction correlates with the quality and the extent of the available inspection data. The following differentiations can be made in the condition- and substance predictions:

- Section not inspected
- Section inspected once
- Section inspected several times.

The procedure of the section-related prediction is illustrated in the following by means of a case model for the substance prediction of an inspected section.

An inspected, ten-year-old section (pipe material: concrete, DN<700) is given. From the inspection results a substance class of "SC 1.5" was determined on the basis of a continuous classification [7]. Thus, correspondingly in the inspection year (here 2005) the section is in the substance classes "SC 1" and "SC 2" by 50 % each (Figure 8).

The basis for the prediction of the substance development is provided by the age-dependent transition probabilities into the next worse substance class. The transition probabilities are calculated from the network-specific aging functions and are summarized in a transition matrix [11].

In Figure 8 the prediction of the substance development for the exemplary section is illustrated in five-year-steps. The initial distribution represents today's substance value distribution (front group of bars). The probability of a failure (EA bar) increases
continuously. In 2035 the section will belong to substance classes "SC3" or "SC 4" with a probability of 12 % or 18 %, respectively, whereas the risk of a breakdown already amounts to 67 %.

2.2.3 Prediction quality

Since the long-term prediction presents a vital basis of modern rehabilitation planning, it is indispensable to ensure a corresponding prediction quality. On the one hand the predictions are to provide similar results with similar data and thus are to be steady. On the other hand the results are to illustrate the real network aging process as precisely as possible.

The prediction quality can be checked with the help of available re-inspections by ex-post-predictions. For that purpose the substance development is verified by comparing the values that were predicted on the basis of the first inspections with the real values of the re-inspections.

At the same time a further improvement of the prediction quality is enabled for repeatedly inspected sections since in those cases also a consequential distribution (2nd inspection report) is available besides the initial distribution (1st inspection report).

2.3 Strategic analyses

The prediction model "STATUS-Sewer" forms a solid basis for analyses of effectiveness of decisions for rehabilitations. By giving budget sizes, ecologic and hydraulic requirements as well as further network-specific limiting conditions, various strategies can be investigated exhaustively concerning their effects on the substance development, the rehabilitation costs, the fees etc.
Here the prediction of the network-specific aging processes allows to follow the future need for rehabilitation and effectiveness or economic efficiency of the chosen rehabilitation strategy for different planning intervals and to evaluate them. Simultaneously, statements with regard to the future can be deducted concerning the necessary employment of financial and human resources so that the discussion between technical and commercial decision-makers receives a reliable basis.

The process of finding a strategy is carried out by evaluating several rehabilitation strategies (cf. DWA-M 143-14 [1]) and by the long-term cost-and-condition developments caused by them. In this way an optimum course of action that presents an acceptable compromise between competing target quantities.

In the following the developments of various indicators as a consequence of a "moderate strategy" with different budget sizes are explained in an exemplary way. For the analyses the drain and sewer system of a German medium-sized town was taken as a basis.

**Rehabilitation costs**

The annual rehabilitation costs are composed of repair-, renovation- and renewal costs. The available budget is employed in correspondence with the determined intervention criteria. The annual total rehabilitation distances as well as rehabilitation distances related to the various kinds of rehabilitation vary due to the network-specific aging processes. Figure 9 shows that from 2017 an annual budget of 2.5 % of the replacement value (RV) does not need to be fully overspend since the backlog of rehabilitation has already been reduced and the need for renewal decreases in the medium-term. If a budget of 2.0 % of the replacement value is taken as a basis, only from 2030 onwards a budget surplus develops. A budget of ca. 1.3 % of the replacement value would be completely used up in the period under observation to 2035.
Substance development

Figure 10 shows the development of the network's substance value by using various budget sizes. The monetarized substance value orients at the "original value" or the replacement value of the sections. Starting from the constructional substance and the remaining technical utility duration of the sections, the replacement value is reduced. The reduction is calculated from the proportion of the remaining utility duration on the total utility duration according to DWA-M 143-14 [1].

From Figure 10 it can be clearly extracted that a budget size of 1.3 % of the replacement value leads to a continuous depletion from a long-term point of view. A budget employment of 2.5 % of the replacement value leads to a clear development of substance till 2020. Since the need for renewal decreases afterwards and the full budget no longer needs to be used for rehabilitation measures the substance value decreases after 2020. A relatively continuous development of substance to 2030 with subsequent consolidation phase is achieved with an annual budget size of 2.0 % of the replacement value.

Sum of costs consisting of rehabilitation costs and monetarized loss of substance value

In order to receive a combined evaluation quantity in the evaluation of different budget sizes the rehabilitation costs and the monetarized loss of substance value are overlapped. In this way the economic effectiveness of a chosen budget size is clarified. In Figure 11 the cumulated sum of costs consisting of the rehabilitation costs and the monetarized loss of substance value can be seen. It can be noticed
clearly that an annual budget use of 1.3 % of the replacement value in the network looked at presents the most cost-intensive variant.

![Graph depicting cumulative cost sum consisting of rehabilitation costs and monetarized loss of substance value](https://example.com/graph1)

**Figure 11** Cumulated sum of costs consisting of the rehabilitation costs and the monetarized loss of substance value

### Risk of failure

The risks of failure in the drain and sewer system as a result of the different budget settings are illustrated in Figure 12, which presents the relative changes of the failure risk in the prediction period related to 2005. The analysis shows that an annual budget employment of 1.3 % of the replacement value causes a clear increase of the risk of failure. If 2.0 % of the replacement value per year is available as a rehabilitation budget, the risk of failure from 2020 can be reduced to below today's level, whereas an annual budget of 2.5 % of the replacement value continuously leads to a higher level of safety in the drain and sewer system.

![Graph illustrating relative changes of failure risk](https://example.com/graph2)

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Prognostic determination of fees and tariffs

Important for the long-term planning of net-management strategies is the forecast of the development of fees and tariffs, as they impact the customer behaviour and satisfaction. Strategies impacting on this sensitive issue to much risk a customer feedback which may cause the strategy to fail or become less effective. Therefore the forecast of the development of fees and tariffs is should be part of every long-term strategy.

3 Conclusions

Although terms of operating costs, operating stability and service level are most important to network operators, the target of a long-term and holistic net management strategy need to integrate the customers needs and there as one of the first points fees and tariffs.

Such holistic approach, fulfilling the request of German authorities and customers has been developed with the model “STATUS”. Based on reproducible and transparent forecasts, strategies and scenarios the development of the network under different management strategies, can be predicted, giving decision support for the network operators. Solid mathematics allow the long-term planning of almost every single key factor of a utility such as budgets, service levels, tariffs, costs, serviceability and so on.
Bibliography


