Selecting and scheduling infrastructure rehabilitation projects

R. Baur and I. Kropp
Technische Universität Dresden, Fakultät Bauingenieurwesen, Lehrstuhl Stadtbauwesen, Nürnberger Straße 31A, 01187 Dresden (E-mail: ingo.kropp@mailbox.tu-dresden.de)

Abstract
Targets for the condition and performance of water supply networks can be formulated from quantitative needs as well as from the demand for the quality and reliability of drinking water networks. To reach these objectives, a public or semi-public utility needs to invest in system maintenance and rehabilitation. For the system analyst it is difficult to give specific action threshold values for each indicator describing the network performance. Preferences differ and interdependencies between criteria do not allow, by conventional scoring models, determination of those projects which are the most efficient. Another method is presented for ranking rehabilitation projects according to multiple criteria with respect to efficiency. The development of the procedure and its implementation in software is part of a research project funded by Deutsche Forschungsgemeinschaft (DFG).

Keywords
Decision support; geographical information system; rehabilitation; water distribution networks

Rehabilitation needs of water supply systems
Between 1990 and 2000, the water utilities in Germany spent about 60% of their total investments i.e. €17 billion, in the extension and rehabilitation of their networks (BGW, 2001). For the planning of rehabilitation investments in drinking water networks it is important to know the order of magnitude of future rehabilitation needs. Annual rehabilitation needs arise from pipes which come to the end of their service life. The annual needs depend on the mileage and age of the pipelines in the system, the expected lifetime of pipe types which is largely determined by the deterioration process of the pipe, and standards set for the level of service in the system.

For the quantification of future rehabilitation needs, the cohort-survival model and the Herz-distribution for the service life of infrastructure elements (Herz, 1996, 1998) are appropriate tools implemented in the KANEW software (KANEW, 2001). This software calculates the future rehabilitation length of pipe types, year-by-year, and provides additional modules for what-if strategy simulations and economic analysis of strategies against the do-nothing option. Figure 1 shows the typical age and material structure of an East German water utility and the rehabilitation needs for the year 2000 up to 2100, calculated using KANEW. A survey among East German water utilities yielded average annual rehabilitation needs in the order of 2% of the total water distribution network length (Herz, 1999). The question now is how to identify those rehabilitation projects which should be realised within the utility’s budget for rehabilitation investments.

Cost efficient rehabilitation projects
Pipe sections are candidates for the annual rehabilitation programme in the case of an unacceptable technical and functional state, or if the costs of maintenance and repair surpass the costs of rehabilitation. Obvious signs of ageing are increasing rates of pipe breaks and water losses, reduced hydraulic performance, significant head losses or discoloured and polluted water. While the last indicator is demanding immediate rehabilitation action, pipe breaks and leakage can be accepted or not. So, it is not just a technical but a political
and economic decision, when to rehabilitate and whether to re-line or replace a deficient pipe. The objective of a pro-active rehabilitation policy is to identify those projects that would have the most positive effects on the network performance, in the short and in the long term (Baur and Herz, 1999). Possibly the decisionmakers know quite well which parts of the network urgently need rehabilitation. But there is the problem of limited budgets, which may be caused by declining revenues due to a politically and socially restricted water price in combination with reduced consumption in recent years, and by relatively low labour productivity due to overstaffing. So, it is necessary to select options which promise the highest cost-efficiency.

The setting up of a rehabilitation plan is a multiple criteria decision. For the utility, the objective of a pro-active rehabilitation planning is the improvement of the network condition and the reduction of the operational costs. For the customer, product quality, reliability of water service and its price determine the worth of the infrastructure. Frequent traffic interruptions and noise due to repair work without warning do affect the image of a water utility. Relevant criteria very quickly reach a double digit number. In the decision rules of the German technical standards for each pipe section, between 1 and 8 weighting points are assigned to the number of 24 criteria. Priorities for rehabilitation are set according to 3 decision rules (DVGW, 1997): A single criterion with 8 points or a total sum of 10 weighting points with at least one criterion with 4 points or a total sum of 12 weighting points.

Such scoring models, such as the multi-attribute decision making method, the cost-benefit analysis or their simplified variations, transform criteria by goal functions into points or monetary units and assign weights to criteria in order to consider their relative importance. In general, the result is an output from a black-box which does not exhaust the engineers’ and other decision makers’ potential. Usually, the decision maker will not know exactly what consequences a specific threshold value for one criterion will have on the performance of other criteria and where the restrictions would be accepted or not. That means his/her preference structure is not predefined but will be developed successively in a learning process. An interactive elimination approach with integrated effect control allows a step-by-step observation of what would happen if a critical demand for the performance of a particular criterion is defined, e.g. the sum of the total costs if all pipes would be replaced with a maximum number of breaks on a defined pipe length over the last two years. With the results of the “what-if” analysis, those projects which are not promising a sufficiently high efficiency can interactively and successively be eliminated.

Figure 1 Water mains inventory and forecast annual rehabilitation needs (KANEW, 2001)
The interactive elimination procedure

The interactive elimination procedure with effect control for infrastructure investments was introduced for the prioritisation of corridor alternatives in the German federal road investment plan (Hochstrate, 1987). It is modified here for the rehabilitation planning of an drinking water infrastructure network. In the beginning, all pipes are potential candidates for rehabilitation. The procedure starts with the presentation of the total network and all criteria ranges, from the lowest to the highest value, defined as the initial “solution corridor”. The number of projects will be reduced step-by-step by setting limits for particular criteria values until a break-off value at a pre-defined criterion is reached. In most cases this will be the budget limit, where the elimination process comes to an end (Figure 2).

For example, the determined range of the break rate in pipe sections could start from “no breaks per 100 m in the last two years” up to “4.3 breaks per 100 m in the last two years”. The break rate can be presented in a density distribution for all pipe sections and in a classified topical map. A first limit set might be “0.8 breaks”, which means all pipe sections with less than 0.8 breaks per 100 m in the last two years would be eliminated from the solution corridor and not be considered in the rehabilitation plan. Before the pipe sections are eliminated, the effect control, checks whether the elimination step reduces the solution corridor by pipes with a undesired performance at other criteria.

In the example, there could be pipe sections in the network with less than 0.8 breaks per 100 m in the last 2 years breaks, but located in an area where frequent pressure shortfalls recently gave rise to serious customer complaints. If hydraulic analysis yields problems in these pipe sections, they are obviously candidates for rehabilitation and should not be removed from the annual rehabilitation plan and the threshold of “0.8 breaks” must be lowered. In the same way, elimination criteria can be used in combination, e.g. if the utility’s policy is just to spot-repair and not to replace or to re-line metallic pipes which are younger than 20 years. In this case, all pipe sections fitting these demands could be eliminated. Combinations of criteria limits can be linked with AND or OR. Thus, the interactive elimination procedure with effect control, works like a funnel where each elimination step has the function of a refining screen for the most efficient rehabilitation projects. In Figure 3, the formal structure of the elimination process is outlined in a flow chart.

Application

The interactive elimination procedure is facilitated in the modular Spare-I-Net software for planning the annual rehabilitation of infrastructure networks. Different tools are developed

![Figure 2 The elimination funnel](https://iwaponline.com/ws/article-pdf/2/4/43/407670/43.pdf)
for the presentation of criteria, including diagrams and topical maps. The software is not part of a utility’s asset management database system nor is it integrated in a geographical information system. However, a well organised and maintained database of the network including technical and geographical information is helpful and should be available. The application provides recommendations for a criteria catalogue and additional data in the decision process and it consists of two modules: the data management tool DMT; and the annual rehabilitation planner ARP.

Criteria
The recommended criteria for the selection of a pipe for rehabilitation are taken from a survey on the “Guidelines for Assistance for the Rehabilitation of Water Distribution Systems” (DVGW, 1997) among water utilities in Germany and other European countries. The criteria very closely correspond to those considered in the working package 3 intermediate report on “Decision Support for Annual Rehabilitation Programmes” (Le Gauffre, 2001) of the CARE-W project, a European research consortium with focus on “Computer Aided Rehabilitation of Water Networks” (CARE-W 2001). The criteria quoted for the decision vary from utility to utility due to different problems in the network and due to different rehabilitation policies. So, the aim was to develop a decision support open for information of different quality and accuracy, stored on different media. The recommended criteria catalogue is divided into four sections: technical criteria; economic and utility specific criteria; other criteria; and network data. In the fourth section, criteria for the evaluation of the whole network for a long-term strategy are listed which are not utilised on a pipe level, but should be very useful for benchmarks of rehabilitation programmes. Some of the data fields listed in Table 1 are not decisive criteria but variables required for criteria calculations, like the pipe section’s length (Kt1 in Table 1).

The presented set of criteria is not yet necessarily complete, and it can be modified and
reduced individually according to data availability and the preferences of the decision maker. The elimination process can be interrupted whenever the need of further information or more detailed criteria is emphasised. Thus the interactive elimination procedure supports in a comprehensive way the efficient use of available data in the decision process.

**DMT: the data management tool**

The DMT is controlled by the menu structure of the software and it prepares and organises the available data for processing the ARP. The data management includes the definition of units and the import and the editing of data. After the import of network data the programme starts with the recommendation of a criteria catalogue. While available data are listed conventionally, fields of missing data are set off. The decision maker must decide whether the effort to collect the missing information is worthwhile and would essentially improve his decision, or if it would be possible to set up the rehabilitation plan just with the available data. For the definition of the criteria catalogue which will be used in the elimination process, criteria can be chosen from the pre-defined criteria catalogue or added according to additional data. After the definition of criteria the values for the budget limit, unit costs and “alarm values” for control criteria must be fixed. The elimination process comes to an end, when the budget limit is reached. The costs of all projects in the rehabilitation plan are calculated from the pipe length by average unit costs. If an alarm value for a particular criterion is set, the elimination process of the ARP will be interrupted in the case of elimination of a project which falls under the alarm value.

**ARP: the annual rehabilitation planner**

In the next step, the ARP is started. The ARP is the implementation of the interactive elimination procedure presented previously. Figure 4 shows the main screen for running the ARP. The top part of the screen provides general information on the status of the control criterion and progress of the elimination process. The ARP main body consists of two parts. The left-hand side shows the criteria catalogue, classified by the three sub-categories: technical, economic and external criteria. A check-box each criterion can be selected for the current elimination step. For selected criteria, the field on the right side of the description is active, and it is possible to set limits for the criterion value. Graphical presentations of the solution corridor of criteria are available by triggering the buttons on the right side of the criteria description in order to support the decision process. On the right side of the main body a graphic window allows the observation of criteria and the state of the elimination process.
process on the map. The map provides the opportunity to distinguish pipe sections which are already eliminated, from those which are still candidates for the annual rehabilitation plan. In the bottom line of the ARP screen there are three buttons which control the elimination process by testing, rejecting and confirming elimination steps. Every confirmation of an elimination step requires an argument in the provided text field. The optional “No Dig” button provides the possibility to pre-define whether a pipe in the final solution corridor should be renovated or replaced. The elimination procedure comes to an end, when the limit of the available budget for rehabilitation is reached.

The ARP automatically produces a report during the course of the elimination process. The report includes the criteria catalogue and all limits set at each elimination step, together with the arguments and potential overstepping of critical values defined as “alarm criteria” in the DMT. In the result, the annual rehabilitation plan is documented in tables and a map.

**Case study**

In a case study, the aim was to schedule the most efficient rehabilitation projects in the drinking water supply system of the water and wastewater company of an East German municipality The company supplies 50,000 people with a total network length of approximately 200 km. As in most East German water utilities, in the recent decade the annual rehabilitation plans mainly were determined by projects of street reconstruction or sewer rehabilitation. The annual network rehabilitation length in recent years was about 1.5% of the network length, non-revenue water is in the order of 30% and the actual network failure rate is in the order of 0.8 failures/km year for distribution pipes with an increasing tendency. If all recorded repairs on distribution pipes, service connections, hydrants and fittings are considered, the failure rate rises to 1.5 failures/km year. For the selection of rehabilitation projects information on the geographical position of a pipe section in the network and the data according to Table 2 were available. In the budget proposals, the amount available for network rehabilitation in 2001 was fixed at €300,000.

According to data availability, the criteria catalogue and the measurement rules for criteria were defined. In cases of imprecise or incomplete data, it seemed appropriate to simplify the scale. For example, the number of service connections per pipe section were
unknown, but using aerial photographs and a city map, the building density was taken as an indicator for service connections and classified into low, medium and high density. Instead of using the information on the condition of each fitting and hydrant, the pipe sections as carriers of information were just classified into two categories, good and not good, according to the condition of the majority of fittings and hydrants in a pipe section. Ductile iron, PVC and PE pipes were eliminated. These materials were in use since 1990 and no failures have occurred on the pipes to date. The next step in the elimination process was setting a limit for pipe sections with a failure rate of 1.6 failures/km year in the last 10 years, which is twice as high as the present network failure rate. All pipe sections with a higher failure rate remained in the set of potential rehabilitation candidates. The rehabilitation length at this step in the elimination process was 24 km of pipes, which included 60% of all 2000 breaks, but was about 7 times the realisable length. Using geographical analysis of the network, three priority areas were identified due to break concentration. Two 250 mm steel pipes next to each other and prone to aggressive soil exhibited heavy external corrosion. In the other main areas cast iron and asbestos cement pipes were the candidates for the rehabilitation plan. Finally, a 200 m asbestos cement pipe section, exhibiting not extremely high failure rates, but constant breaks in recent years was added to the annual rehabilitation plan, because it supplies a hospital. The final result was an annual rehabilitation plan consisting of 3.3 km of pipes.

Due to the fact that information on street reconstruction projects as well as on state-subsidised sewer rehabilitation usually comes suddenly, very often short-term decisions are required. The annual rehabilitation plan set up with the interactive elimination procedure allows easy comparison of the option of co-ordinated work with the reduction of the initially selected projects. In most cases, project co-ordination will be the more efficient solution. Today, many utilities in countries with badly deteriorated infrastructure, such as East Germany or Eastern Europe, rehabilitate their networks up to 95% parallel to other works.

Conclusions

The application of an interactive elimination procedure with effect control is presented for the rehabilitation planning of a urban water supply system. The proposed method does not
require any special data pre-processing, scale transformation or the like, as other decision methods do. Criteria values are used in original scale. Arguments of elimination steps are taken down, so the decision process and the result are transparent and comprehensive to a high degree. The effect control after every elimination step guarantees the consideration of all relevant criteria. The final result is an annual rehabilitation plan which is not produced by a black-box decision support system, but by a decision help with the arguments of the decision-maker.

References


