



COMPUTER AIDED REHABILITATION OF SEWER AND STORM WATER NETWORKS
RESEARCH AND TECHNOLOGICAL DEVELOPMENT PROJECT OF EUROPEAN COMMUNITY

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CARE – S

**Computer Aided REhabilitation of Sewer networks.
Decision Support Tools for Sustainable Water Network Management**

WP6 – Multi - Criteria Decision Support

D19

WP6 conclusive report

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1 Introduction

The CARE-S project is funded by the European Community and aims at the development of methods and software that will enable engineers of wastewater undertakings to establish and maintain an effective management of their sewer and storm water networks, rehabilitating the right sewers at the right time. Working package 6 is dedicated to the development of procedures of multi-criteria decision support in the rehabilitation management.

1.1 Subtasks

TU Dresden is the responsible partner for WP6 Multi-criteria decision support methodologies, which is divided into three sub-tasks, each one with its specific objective, schedule, deliverables and methodology:

- Development of long-term rehabilitation strategies
- Priority setting for rehabilitation projects
- Choosing the right rehabilitation technology

According to the three sub-tasks, this report is structured in one chapter each for the different problems, including example applications within a sub-network of Stadtentwässerung Dresden (SEDD), one of the CARE-S end-users.

Setting rehabilitation priorities is a matter of the type and severity of damage revealed, the remaining substance of the sewer and the external cost of public works in the street. In this decision, economic aspects play a role as great as professional judgement of technical feasibility and future requirements. Therefore, the service life of a sewer is not determined just by technical wear, but also by unit costs of repair and rehabilitation work and by amended technical specifications and standards. Anyway, monitoring sewer condition will be necessary in order to take the right decision at the right time. There is no way of predicting the end of a sewers' service life without reliable information on its actual condition.

Inspection and Condition assessment

State of the art for non man-entry sewer inspection is the optical inspection with cameras (CCTV). With EN 13508, a European standard for codification of inspection results exists, but there are numerous corresponding national and other codes beside. Within CARE-S the effort has been made for developing translation schemes from the national codes into the European standard, in Germany, for example, the ATV M 143-2 code (CARE-S D3 report).

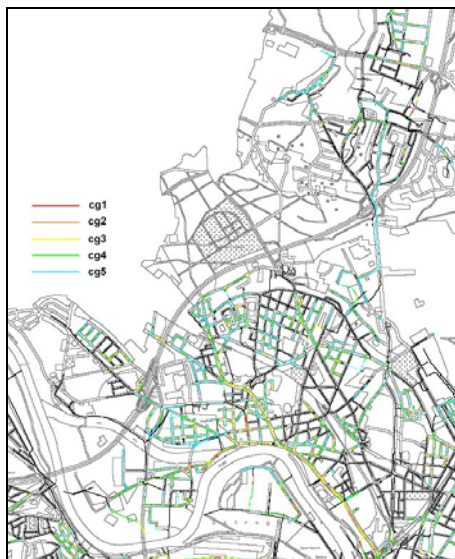


Figure 1: Condition grades of pipes in Dresden-Pieschen

According to the different legal regulations in the Länder, in Germany the complete sewer networks must be inspected within 10 (up to 20) years. In Dresden, approximately 50% of all sewer pipes are CCTV inspected (Figure 1). Some German Länder already allow the selective inspection according to EN 752-5. There are two objectives of a selective inspection of the network: It aims to inspect only those sewers that are likely to approach a critical condition. The second goal is to draw the results of a representative sample to the condition of the whole network, for the calculation of the overall network condition and of an ageing forecast in order to get reliable predictions for the long term investment planning.

Crucial for the prioritisation of rehabilitation projects, as well as for the condition forecast, are the interpretation of inspection results and the subsequent classification of the condition. In Germany, various models for condition classification and corresponding computer software exist. There is the national guideline ATV M 149 and other nationwide used systems (Appendix 1). On the other hand, many locally developed classification systems are applied. This situation is due to two reasons: The national guideline was published late, when some municipalities already have started their inspection programmes and established their own classification system, and additionally there was substantial opposition against the guideline's methodology. The majority of the classification systems are based on the ATV M 143-2 coding system (ATV 1999).

A major issue in the discussion of classification models in Germany is, whether sewers should be classified mainly with respect to the urgency of rehabilitation work due to the severity of a localised damage, or whether the classification should indicate the intrinsic value of the sewer, i.e. the extent of rehabilitation required within a pipe for a more realistic estimate of investment needs. Therefore, the inspection code and the subsequent classification should be capable of answering questions on how urgent the need of rehabilitation at a particular location is, i.e. the definition of priorities, and to what extent the substance of a total sewer pipe length already is used up, i.e. the evaluation of the intrinsic value of a sewer.

Condition classification

Most classification systems define between 4 and 6 condition grades, from the best state for sewers that are in a condition good as new, to the worst state for sewers that require immediate rehabilitation action. Within the definition of priorities, most classification systems focus on structural defects, whereas environmental and hydraulic aspects are considered by fewer classification systems (ATV M-149 1999, Le Gauffre et al. 2002a, for other models see also: Stein 1998, WRc 2002). The final mark, which is equivalent to the resulting priority, is then calculated by mathematical operations with pre-defined rules and weights. The assignment of a pipe to a classified condition grade mainly depends on the most serious localised structural or operational deficiency. Thus, the classification reflects the urgency of the intervention with respect to a particular aspect, e.g. the danger to man and environment, or functionality of the system. Nevertheless, the classification provides no further recommendation whether local repair will be sufficient for the restoration of the sewer's functionality, or whether renovation or replacement of the whole length of the pipe would be justifiable in economic terms.

If the hydraulic capability of a sewer does not meet its requirements due to an inappropriate dimension of the sewer, the pipe could be replaced. Alternatively, operational measures, e.g. the implementation of a runoff control system or the decentralised infiltration of surface waters, could be considered. Priorities for hydraulic aspects can be defined by thresholds, e.g. for the annual frequency of flooding or the capacity ratio of the pipe section. However, it is difficult to include these aspects into an integrated final mark, or condition grade.

Environmental aspects are aggravating factors for the determination of priorities for rehabilitation. For a risk assessment, the external conditions of land use, soil type, groundwater level, water protection zone, etc. must be considered. They could be combined with the detected deficiency type mathematically in a formula or logically in a decision tree. In some cases, the environmental aspect is considered by the definition of a different

intervention class (lower priority of the condition grade) of sewers which are, for instance, located in sensitive areas, e.g. with respect to water protection zones. In the following, the results referring to this type of classification with respect to the urgency of intervention will be denoted as “Condition grade”.

Intrinsic value of assets

Rehabilitation needs in a sewer pipe could arise from severe localised damage or from recurrent deficiencies with longitudinal extension. Whereas repair of localised deficiencies could restore the good condition of the sewer at relative low costs, extended deficiencies might require more expensive rehabilitation efforts. For the long-term planning of sewer network rehabilitation and for the estimation of rehabilitation budgets, a condition assessment is necessary that considers the intrinsic value of the sewer. Hochstrate (1999, 2000) proposes a model, which is adopted by the Baden-Württemberg (one out of the 16 German Länder) “Guidelines for cost-minimised sewer rehabilitation” (MUV-BW 2000), for the classification of sewers into condition groups (CG). They are revealed by the combination of priority classes and condition classes (Figure 2) which are derived from the interpretation of a deficiency profile for the individual sewer pipe (Figure 3). Thus, in the following, the term “Condition class” refers to the intrinsic value of the sewer.

| Priority class | Condition class | | | | | |
|----------------|------------------------------|------------------------|--------------------------------|------|----------------|------|
| | CC 1 | CC 2 | CC 3 | CC 4 | CC 5 | CC 6 |
| PC 1 | 1.CG: Intrinsic deficiencies | | 2.CG: Repair Deficiencies | | | |
| PC 2 | | | 3.CG: Subordinate deficiencies | | | |
| PC 3 | | | | | 4. CG: no def. | |
| PC 4 | | | | | | |
| PC 5 | | (logically impossible) | | | | |
| PC 6 | | | | | | |

Figure 2: Definition of condition groups (CG) for rehabilitation management (MUV-BW 2000)

The deficiency profile plots the position of each deficiency, registered and documented by inspection, over the total length of the reach (Figure 3). Each deficiency is indicated in the net deficiency profile by its condition grade (priority classes, PC), e.g. determined by the evaluation scheme according to ATV M 149, with position and extension. The highest deficiency class defines the condition grade of the pipe, from 6, which is good as new, to 1, which are, for example, collapses requiring immediate rehabilitation. In the gross deficiency profile, each deficiency is covered by a minimum repair length, e.g. 5m. The repair length’s position depends on the relative position of the deficiency to other ones and the distance to the starting and ending point of the pipe. Thus, concentrated deficiencies are covered by a shorter repair length than the same number of deficiencies spread over the length of the pipe.

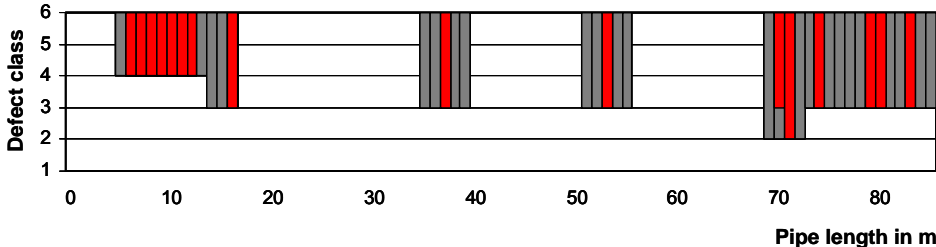


Figure 3: Defect profile of a sewer pipe

The resulting condition class is calculated by the statistical interpretation of the deficiency profile. It corresponds to the deficiency class at which the cumulated gross deficiency length steps over a pre-defined limit, e.g. 30% of the total length of the reach, denoted as intrinsic ratio.

The condition class calculated by the presented model is representing the intrinsic value of the sewer. The assignment to condition groups gives a first estimate of the appropriate rehabilitation measure, whether repair could be sufficient for restoring the condition of the sewer, or whether renovation or replacement should be recommended.

Three evaluative steps are necessary for the presented classification model: the classification of deficiencies, i.e. the interpretation of inspection codes and the subsequent assignment to deficiency or priority classes, the definition of the minimum gross deficiency length, and the definition of the intrinsic ratio. The definition of these values requires further investigation. The model is suitable for the definition of rehabilitation priorities, and for the estimation of the rehabilitation needs.

1.2 Case study

An example application for sub-task 6.3, the strategy development, was taken from the Pieschen sub-network of Stadtentwässerung Dresden (SEDD). The sub-network represents 139 km, or approximately 9% of the total network length of SEDD. Construction periods are well known for the network. Just the decades after World War II are rather assumptive, especially the significant peak in 1960 is most probably due to the assignment of pipes for which the exact installation year is unknown (Figure 4).

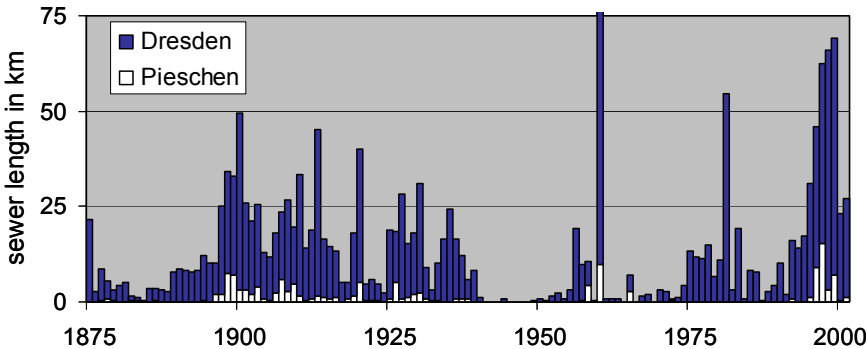


Figure 4: Sewer length in km by construction year for Dresden and Dresden-Pieschen

The sub-network is located in the North-Western part of Dresden on the right hand riverside of river Elbe, and it has been chosen with respect to its possibility of an appropriate hydraulic separation (Figure 5). The covered area includes high density urban areas, industrial and commercial areas, a more rural area in the Northern part, and the Wastewater treatment plant (WWTP, the blue point on the map in Figure 6)

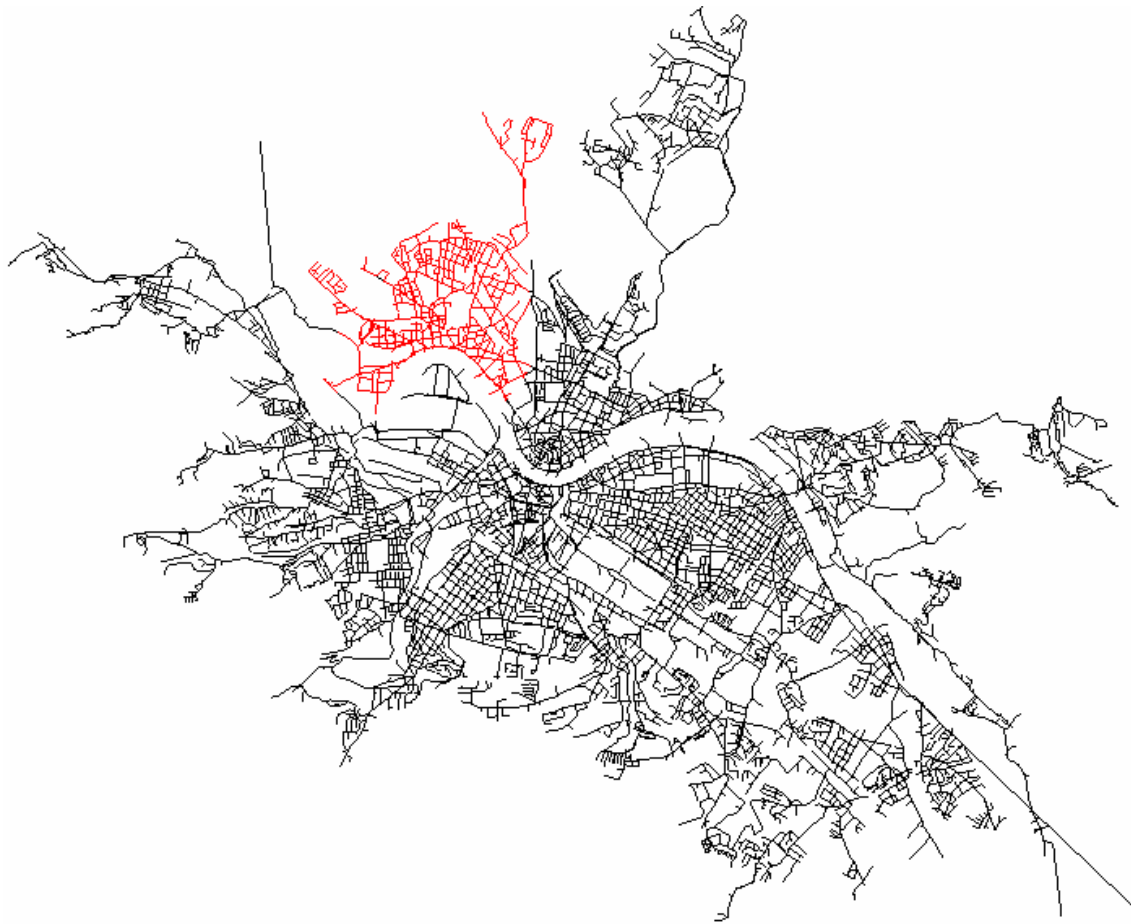


Figure 5: Scheme of the Dresden Sewer system indicated the Pieschen sub-network

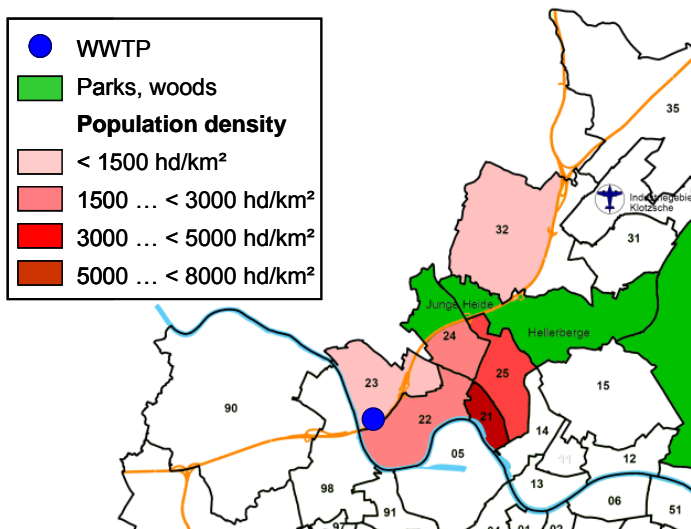


Figure 6: Area covered by the sub-network, indicated are green spaces, population densities of the area of interest and the location of the WWTP

The considered sub-network was partially victim of the big flood event in August 2002. The flooded area indicated in Figure 7 is the calculated result for a 9.24m level of River Elbe without consideration of the impact of flood shelter devices or drainage by sewer pipes.



Figure 7: Theoretically flooded areas in Dresden-Pieschen for a 9.24 m level of River Elbe (www.dresden.de)

The calculated flood area is rather theoretic. In Figure 8, the actually flooded area reported on August 17th, 2002, is indicated, when River Elbe reached a maximum level of 9.40 m.

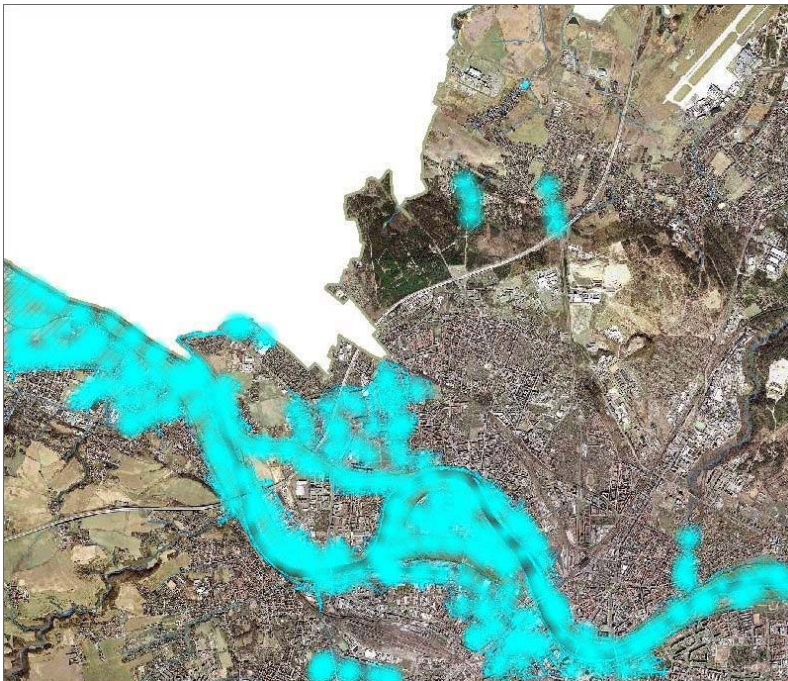


Figure 8: Flooded areas in Dresden-Pieschen on August 17th, 2002, maximum level of 9.40 m of River Elbe (www.dresden.de)

Because all condition information result from CCTV inspections performed before August 2002, failures caused by the flood event cannot be considered within the deterioration model. However, those pipes prone to higher groundwater levels and floods during this event are definitely more likely candidates for future inspection.

2 Decision support methodologies

The objective of a multi-criteria methodology for choosing the best rehabilitation option is to find a transitive¹ overall final order of a finite set of candidates, or to select a finite number of candidates. The candidates here can be different types of rehabilitation technologies for choosing the best one, or different sewer pipes with serious defects for which a priority list must be found, or different strategies, which must be evaluated and ranked according to their long-term benefits. In any case, the candidates must be compared with respect to a number of criteria, by calculating the values e_{ij} for each candidate (Figure 9).

| | Candidates | | | |
|----------------|----------------|----------------|----------------|-----|
| Criteria | P ₁ | P ₂ | P ₃ | ... |
| C ₁ | e_{11} | e_{12} | e_{13} | ... |
| C ₂ | e_{21} | e_{22} | e_{23} | ... |
| C ₃ | e_{31} | e_{23} | e_{33} | ... |
| ... | ... | ... | ... | ... |

Figure 9: Impact matrix

Classification of methodologies

Multi-criteria evaluation methods can be classified either with respect to the final result they produce into ranking, classification, and selecting methodologies, or according to the prevailing evaluation principle into substitution methodologies and elimination methodologies.

Substitution methods

A very popular multi-criteria technique, the method of average weighting, belongs to the substitution methods, also referred to as aggregation or scoring models. Here, the bandwidth of criteria within the impact matrix is reduced. The overall ranking of options is built in three steps:

1. Transformation of all criteria into a uniform scale (normalisation)
2. Distribution of weights, i.e. relative importance or exchange ratios between criteria
3. Aggregation with a utility function for the final ranking order

Usually, aggregation methods are applied which in most cases use a monetary expression or dimensionless point scales for the normalisation. In general, the normalisation and the definition of the utility function are prepared by an “expert”, whereas the only interaction between the decision-maker and the decision procedure is the assignment of weights. Conventional scoring models then apply a simple weighted-sum-rule for obtaining the final result, in terms of priorities, or a ranking order. The problem of these methods is the priority and weighting of the individual criteria, since overrating and underrating of certain aspects is most likely to happen (Vincke 1992). The cost benefit analysis is a sophisticated, but typical substitution method, where all costs and benefits are normalised into the currency scale. The problem of assigning costs to polluted waters, odour, or collapse risks is the well known and often discussed difficulty of this approach (Heinemann 1984, Strassert 1984). An additional aspect and argument against these methods, is the politically accepted incomparability of monetary and environmental or social aspects within decision problems with public relevance (Roy 1985).

¹ A final order of a set of options is said to be transitive if it meets the transitivity condition (e.g. if $A > B$ and $B > C$, then $A > C$). It is said to be linear if there is no cycle of preference involved (i.e. ‘ $A > B > C > A$ ’ is cyclic and therefore not linear. See also chapter 5)

Elimination Methods

The principle of elimination methods is to reduce the bandwidth of options with thresholds (=arguments) by excluding unsuitable candidates. There is no final evaluation, but a stepwise threshold setting at particular criteria for eliminating undesired options. One of the advantages of elimination methods is the possibility that criteria can have different dimensions. A very popular, non-formalised version of elimination techniques is the discussion, or - in its more formalised version - the structured interview, for example applied in the course of urban planning competitions.

The selection procedure consists of three elementary steps:

1. Setting a threshold value at criterion C_1
2. Observing the consequences at all other criteria
3. Confirming (or rejecting) the elimination threshold and setting the next threshold at the next criterion

The process is repeated until a break-off limit (e.g. a given budget) is reached.

Within elimination procedures, effect control and reasoning initiate a process of balancing advantages against disadvantages, which leads step-by-step to a common decision. Thus, elimination procedures have rather the character of a decision support system than decision-making, like the substitution methods do.

Multi-criteria pairwise comparison

For a limited number of candidates, a formalized pairwise comparison can be applied with respect to multiple criteria. A typical example for the application of a formalized multi-criteria pairwise comparison is site selection in logistics, e.g. power plant or destructor location. The methodology has its limits in the number of candidates, as the number of pairwise comparisons increases rapidly: for n candidates, the number of comparisons is $n*(n-1)/2$. The result is an overall ranking order of candidates. Like for the elimination methods, criteria need not to be normalised into one common dimension.

ELECTRE

ELECTRE ("*EL*imination *Et* *Choix* *Traduisant* *La* *RE*alité" = elimination and choice translating the reality) is the French approach to multi-criteria decision methodology, restricted in the planning of engineering infrastructure projects, its first apparition being in the sixties. Most versions have been developed by Roy and associates (Roy 1993). The method manipulates the criteria into "concordance" and, if evaluations are richer than ordinal rankings, "discordance" matrices. Options are pair-wise judged. The concordance set shows all criteria where an option is preferred or equal to another, while the discordance set shows the reverse outranking. Several procedures are available for sorting, ranking, selecting.

Contrary to the optimization of an economic function, the multi-criteria analysis is not formalized mathematically indeed. It uses models built partially on inevitably restrictive mathematical hypotheses and partially on information collected by the decision-maker. The main characteristic of the analytical multi-criteria methods is to formalize the preparation of the decision by improving the transparency of the decision process and by defining and clarifying the decision-maker responsibility.

In CARE-W WP3 report *Decision support for annual rehabilitation programmes* (Le Gauffre et al. 2002), it is a sorting procedure that was applied: ELECTRE tri. Here we would propose a ranking procedure ELECTRE III: The objective of ELECTRE III is to rank options, since "best" until "less good". The approach used by ELECTRE III is based on:

- concordance and discordance concepts (allowing to take into account the collective self-reliance of the decision-maker in a fine way),
- two types of outranking : strong and weak,
- an outranking algorithm with two simple ordering : direct and reverse (Diab 2000).

Procedures for multi-criteria decision support in CARE-S

The objective of multi-criteria methodologies in CARE-S WP6 is to provide decision-support for three different types of decisions: Developing a long-term rehabilitation strategy, selecting cost-efficient rehabilitation projects, and choosing the best rehabilitation technology. Different procedures of multi-criteria decision support are analysed, that have been applied in the past to decision problems in the field of infrastructure rehabilitation.

The development of long-term strategies is supported by the application of the WP2 structural deterioration model GompitZ (Le Gat 2005). It has been integrated into a framework for the calculation of alternative strategies that can be compared in a systematic way to each other. An example is given for the consideration of predictable performance indicators within the evaluation of rehabilitation strategies. Cost-efficient rehabilitation candidates are selected by the support of an interactive elimination procedure. Here, cost-efficiency is determined by the most positive impacts e_{ij} achieved by all rehabilitation candidates realised within the frame of a given budget. The choice of the best rehabilitation technology for a selected rehabilitation candidate is supported by a formalised balancing and ranking procedure.

Conclusion

The substitution methods offer a logical structure of procedures, which determine a unique result by mathematical operations. However, methodological problems arise from the numerical scores and weights assigned to individual criteria. They blur the contribution of individual criteria to the overall score by compensating for smaller and larger contributions from different criteria. However, there is no way to balance polluted water with clean air or destroyed natural landscapes with quiet vehicles. Another drawback of aggregation procedures is their lack of transparency in the decision process.

Thus, approaches which rely on aggregation are quite suitable for an evaluation that is based on criteria which are measured on a uniform scale, e.g. in monetary terms, since the balance of costs and benefits (or savings), appears to be rather accurate.

The advantage of the concordance analysis (e.g. ELECTRE methods, Roy 1985) compared to scoring models is due to the comparison in pairs of relative advantages and disadvantages of candidate options. There is no direct compensation of criteria by a utility function. However, a number of model parameters must be set/defined by the user (namely indices and thresholds, and the criteria weights).

Multi-criteria decision problems where options must be compared by characteristics with mixed scales are more likely supported by elimination procedures that evade the black-box approach of non-transparent interdependencies determined by criteria weights, normalisation functions and a utility function

For the evaluation of rehabilitation technologies in CARE-S, the formalised balancing and ranking procedure (Strassert 1995) was chosen and will be compared with an Electre procedure. Both methods will begin with a pre-elimination step.

The objective of decision-support systems is the priority setting of network rehabilitation projects. It can be emphasized that a universal preference structure does not pre-exist. However, this would be necessary to assume for the application of substitution methods. This leads to the choice of a procedure that supports the subsequent development of the decision makers' preferences in an interactive and iterative process (Strassert 1984). The interactive elimination procedure is an appropriate approach that has been proved its practical relevance for infrastructure planning in several case studies: for the German federal roads development planning (Hochstrate 1986) or the development of a rehabilitation plan in a water supply network (Baur 2003). It is preferred to the ELECTRE tri procedure applied in CARE-W due to its higher flexibility with respect to the type and number of decision criteria, their measurement scales, and the higher degree of transparency in the decision process.

3 Rehabilitation programmes and strategies

Investments in sewer rehabilitation must be based on inspection and evaluation of sewer conditions with respect to the severity of sewer damage and to environmental risks. This chapter deals with the problems of forecasting the condition of sewers in a network from a small sample of inspected sewers, and the development of an appropriate rehabilitation strategy for meeting certain objectives.

Key issues of strategic or long-term rehabilitation planning of a sewer network are:

- Forecasting the future condition of sewer pipes by deterioration models
- Determination of deterioration rates and the associated rehabilitation needs for
(a) maintaining the actual condition of the network in the long term
(b) reaching an improved level of service within given time horizon
- Forecasting performance indicators of the network for different strategies (scenarios)
- Evaluation of different scenarios, and choosing the best rehabilitation strategy

Within CARE-S, condition forecasts are performed using the GompitZ model (Le Gat 2005). Transition functions from one into the next poorer condition class are empirically derived from a sample of inspected sewer pipes. The transition probabilities are used to forecast the future condition of sewers. By the same procedure, transition functions have been calibrated for sub-samples of different types of sewers. With these transition functions, the most probable date of entering a critical condition class can be forecast from pipe characteristics, such as material, period of construction, location, use for waste and/or storm water, profile, diameter and so on.

Data set

Obviously, it is inefficient to monitor permanently the condition of the complete sewer network. In order to prevent sewers from collapse, choke, wastewater overflow or exfiltration and groundwater infiltration, the state of the sewers must be inspected, not necessarily at regular intervals but in due time before serious damage occurs. A representative sample of the network pipes should be inspected for getting an idea of the condition of the overall network, and in order to develop a strategy against its deterioration. Sewers are deteriorating slower or faster under specific local circumstances. So, their condition is not determined by age alone. There are variations in material, load, stress, wastewater and subsoil characteristics which have to be considered as factors influencing the process of sewer deterioration. Procedures for how to create a representative data set from limited inspection data are discussed for example in Sjøvold et al (2005) and Baur and Herz (2001). A detailed statistical description on how to select sewer pipes for a selective inspection plan and on the subsequent estimation error of the condition of the total network is discussed in BMB+F (2004).

The efficiency of sewer inspection is greatly improved if failure prone sewers were inspected more frequently and others at larger intervals. In other words: The same risk level could be guaranteed with a smaller amount of inspection; or, with the same inspection cost, the risk of failures could be reduced if local knowledge on specific sewer deterioration is used systematically for inspection planning. A general rule, how to stratify the sample, cannot be given. However, in most cases the main items for distinction will be material (concrete, clay, brick, plastic,...) and construction period. In Dresden, for instance the following periods have been chosen: before 1900, 1900-1940, 1940–1989, after 1990. The user of the GompitZ model is free to define the types of sewer pipes. The stratification variables investigated for the application of the GompitZ model in Dresden-Pieschen are material and construction periods (Figure 10, Table 1).

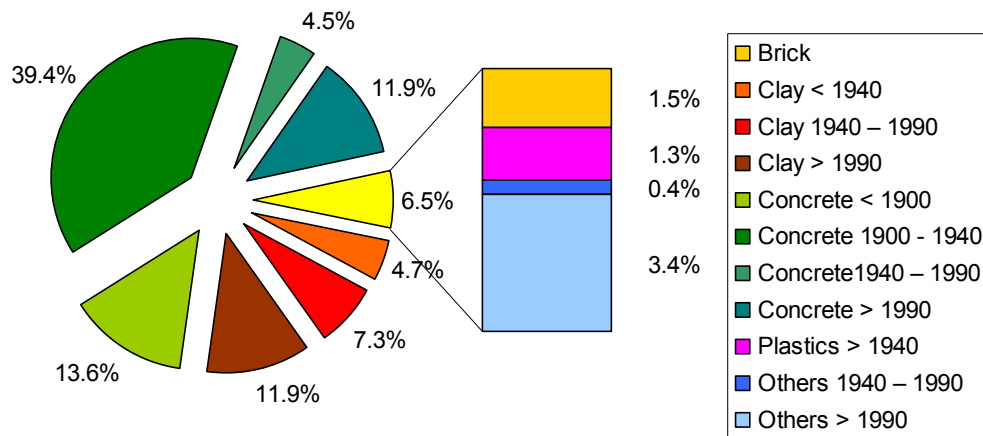


Figure 10: Sewer pipes by material and construction period in Dresden-Pieschen

Plastic pipes are mainly made of PVC. The group of *other* materials consists mainly of asbestos cement pipes installed in the 1960ies (with no inspection results available), and ductile iron pipes installed in the 1990ies.

Table 1: Percentage of pipes by material and construction period, and ratio of CCTV inspection

| Material | Construction period | Length in km | Length [%] | inspected |
|--------------|---------------------|--------------|------------|---------------|
| Brick | | 2.1 | 1.6 % | 24.7 % |
| Clay | < 1940 | 6.6 | 4.7 % | 21.6 % |
| | 1940 – 1990 | 10.1 | 7.2 % | 50.8 % |
| | > 1990 | 16.6 | 11.9 % | 51.3 % |
| Concrete | < 1900 | 18.9 | 13.6 % | 42.6 % |
| | 1900 - 1940 | 54.8 | 39.4 % | 58.4 % |
| | 1940 – 1990 | 6.3 | 4.6 % | 20.4 % |
| | > 1990 | 16.6 | 12.0 % | 51.3 % |
| Plastics | > 1940 | 1.8 | 1.3 % | 33.6 % |
| Others | 1940 – 1990 | 0.5 | 0.4 % | 0 % |
| | > 1990 | 4.7 | 3.4 % | 81.5 % |
| Total | 1828 - 2001 | 139.0 | | 51.7 % |

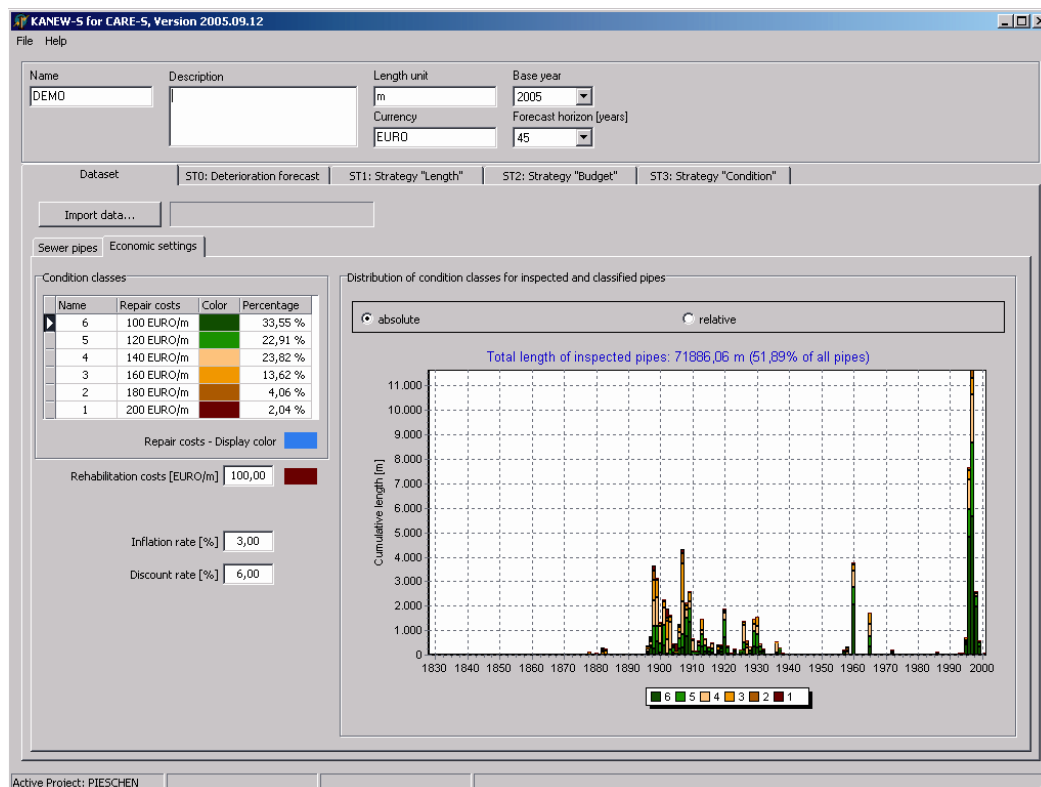


Figure 11: Sewer pipes by material and construction period (application screen)

Condition forecast with GompitZ

A detailed description of the non-homogeneous Markov-chain approach in CARE-S, GompitZ, is given in Le Gat (2005). The principle idea behind Markov-chains is to determine the probabilities of the transition from one condition state into the next. For example, the probability to be in condition grade 3 at a certain time is a function of the transition probability from condition grade 2 to 3, the transition probability from condition grade 3 to 4, and the probability to remain in condition grade 3. The probabilities are calculated by the statistical analysis of asset data, using information either for stratification of the sample or as explanatory variables. The phrase "non homogeneous" here means that transition probabilities are time dependant. The condition forecast is calculated by using a Weibull distribution. The model can use any kind of variables for the analysis. The minimum information required is data on:

- PipeID
- Construction year
- Inspection year
- Length
- Condition grade

Any number of variables can be added, as long as the information is complete for all pipes. Then, the variables explanatory vector is calibrated with empirical data from the random inspection sample. Explanatory variables available from the case study, which have been used for calibration, were:

- dimension (height in mm)
- sewer type (fowl, storm, combined)
- depth (average in m)
- under groundwater table (yes/no)

Finally, for each pipe, year by year the probabilities of staying in the different condition grades are calculated:

PipeID;year;p(1);p(2);p(3);p(4);p(5);p(6)
 Pipe0020;2005;0.485272;0.362755;0.110884;0.033396;0.007693
 Pipe0020;2006;0.449517;0.383841;0.121303;0.036835;0.008504
 Pipe0020;2007;0.413550;0.404113;0.132389;0.040560;0.009387
 Pipe0020;2008;0.377670;0.423249;0.144144;0.044591;0.010347

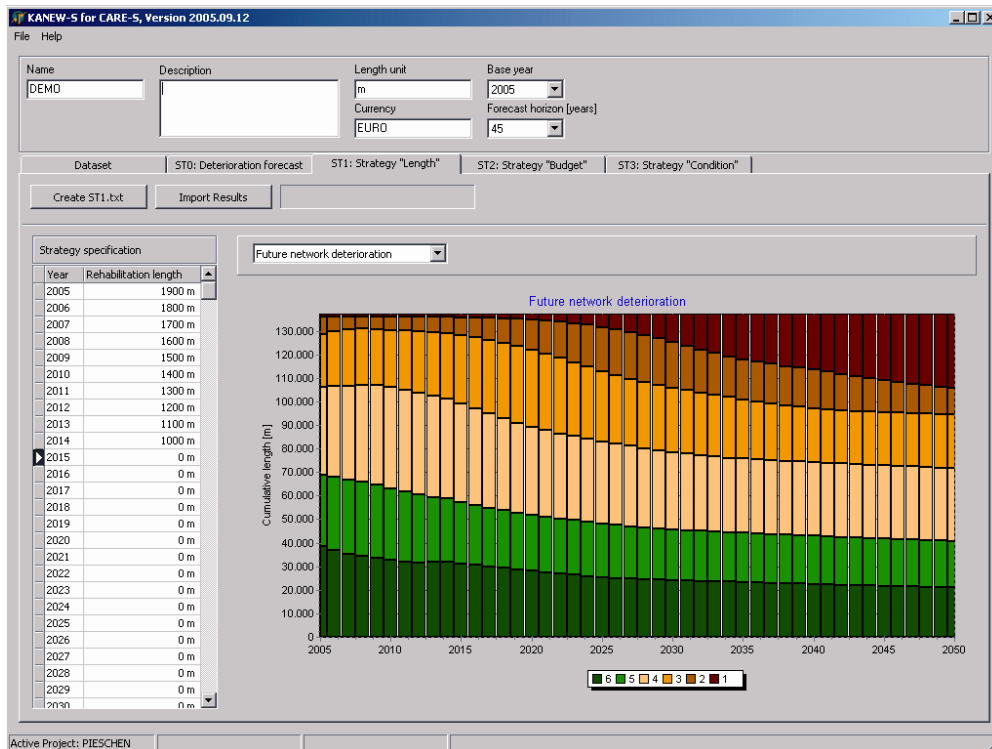


Figure 12: Forecast condition probabilities (application screen)

Options for future rehabilitation strategies

The condition forecast itself assumes a “zero case” in which no rehabilitation is carried out in the future, and the network deteriorating is “undisturbed”. Three types of intervention are defined as potential rehabilitation strategies:

1. Length driven strategy
2. Budget driven strategy
3. Condition target strategy

The first two types of strategies assume a given length or budget for a certain planning period. Within the third strategy, for a given period, e.g. 10 years, a certain deficiency (e.g. pipes in the worst condition grade), shall be reduced, in order to achieve a certain service level, that shall be kept in the long-term.

Example for the consideration of predictable PI: Infiltration

In a joint study of WP3 and WP6 (Schulz/Baur/Krebs 2004), infiltration volumes and infiltration likelihood has been cross analysed with the assignment to condition grades of pipe types. In addition, the subsequent potential reduction of infiltration volumes has been considered within a hydraulic model for calculating the effects on CSO performance and WWTP inflow. Large diameter concrete pipes show a exponential correlation between their degree of deterioration, respectively condition grade, infiltration rate, and the pipe length

affected by groundwater (Figure 2). How far this correlation is caused by the assignment of pipes to condition grades 3, 2 and 1 due to observed infiltration will be subject to further data analysis (Rutsch/Uibrig 2003). In addition, infiltration is also influenced by other factors, for instance the additional load on these pipes due to groundwater pressure, which is considered in the leakage approach applied by Karpf/Krebs (2004), changing loads due to variations in the groundwater level, and others.

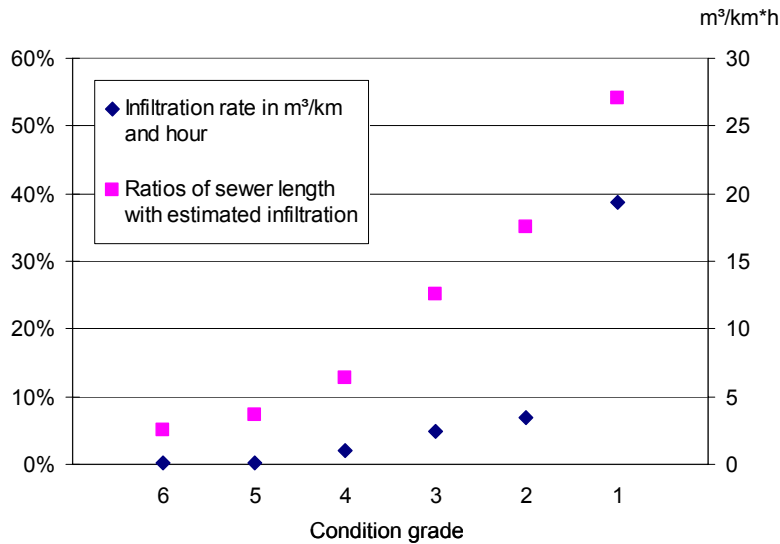


Figure 13: Infiltration length and infiltration volumes against condition grades for large diameter (> 800mm) concrete pipes (Schulz/Baur/Krebs 2004)

In general, the application of a deterioration model using condition grades could be suitable for the calculation of future infiltration rates of parts of the network. Thus, rehabilitation strategies could focus on critical areas in the network, where infiltration volumes should be reduced. The assumption of reducing infiltration rates by a certain rehabilitation length is limited, because the water will probably find other ways to enter the system if leaky sections are tightened, and in addition, that the number of pipes prone to groundwater is limited. On the other hand, the deterioration model could simulate the increase of infiltration rates in ranges into the system due to its higher likelihood of receiving groundwater for particular condition grades. According to the ageing forecast, the ratio of large diameter concrete pipes deteriorated to condition grade 3 or worse, and thus prone to higher infiltration, would reach approximately 80% of the total length of the sub-sample within the next three decades (Figure 6.7).

With respect to their infiltrating lengths, large diameter concrete pipes of condition grades 2 and 3, are in the average 2.7 times more likely to exhibit infiltration than those of condition grades 4 and 5. Specific infiltration rates into the pipes of condition grades 2 and 3 are 2.1 times higher than in the respective pipes of condition grades 4 and 5. So, as an input parameter for the integrated model, a factor for the infiltration rate of the deteriorated network could be derived for the comparison of rehabilitation with the “do-nothing” option. This factor may be in the range of 1.4 to 1.8 times of the actual infiltration rates.

Beside other criteria, the performance of the system has been assessed for CSOs by the calculation of the number of overflow spills, the overflow volume, and the duration of overflows, as a function of the infiltration rate. The parameter has been varied between 0%, 40%, and 80% additional volume compared to the dry weather flow.

Figure 14 shows the simulated influence of infiltration on the overflow volume and duration. The various criteria to assess the effects of the CSO do not always coincide in describing the performance of the overflow structure and are affected differently by the increased input of extraneous water.

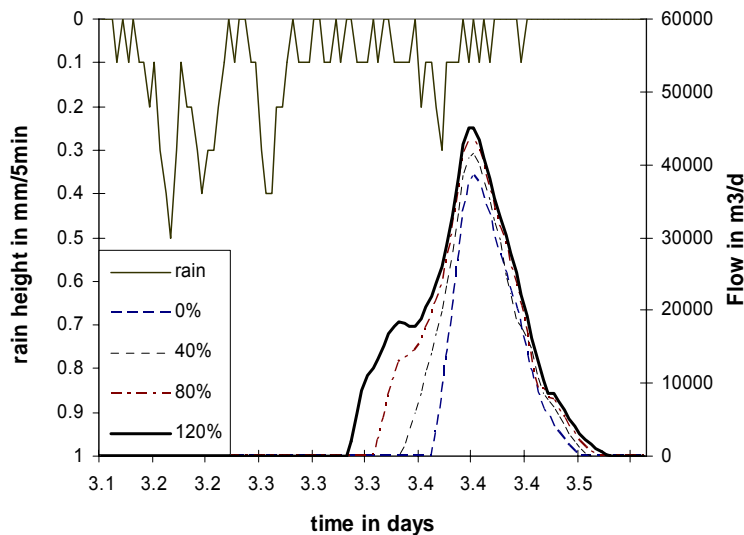


Figure 14: CSO flow as a function of the extraneous water rate (Schulz/Baur/Krebs 2004)

Figure 15 to 24 show three criteria applied to a virtual test catchment with three overflow structures (Structure 1, Structure 2 and Structure 3) with retention tanks. The acute impact of CSOs can be expressed by analysing the minimum oxygen concentration, the maximum ammonium concentration, and the duration of the violation of the threshold value (Figure 25). In this analysis thresholds have been set to

- minimum oxygen concentration = 5 mg/l
- maximum ammonium concentration = 4 mg/l.

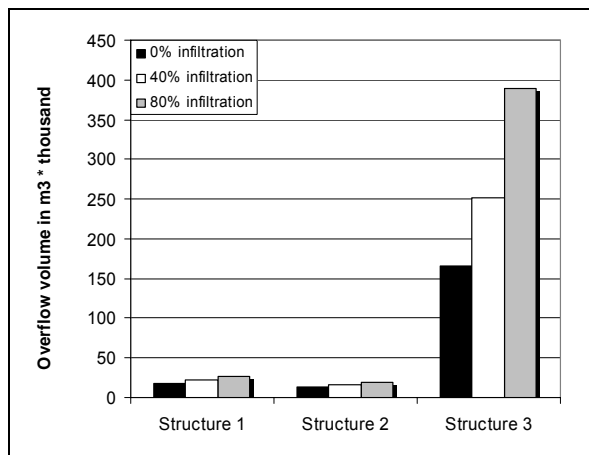


Figure 15: Overflow volume

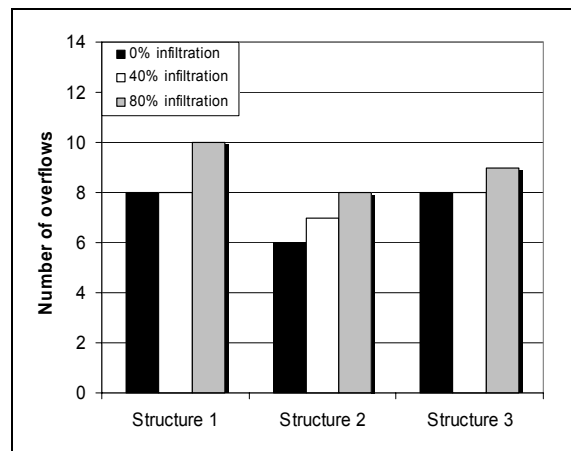


Figure 16: Number of CSO spills

The effect of infiltration volumes on the maximum concentration of NH_4^+ and on the oxygen minimum is not very distinct compared to the absolute values. However, the duration of the critical concentrations is heavily affected. This is an important factor, since the evaluation of the acute impacts is based on two parameters, concentration and duration.

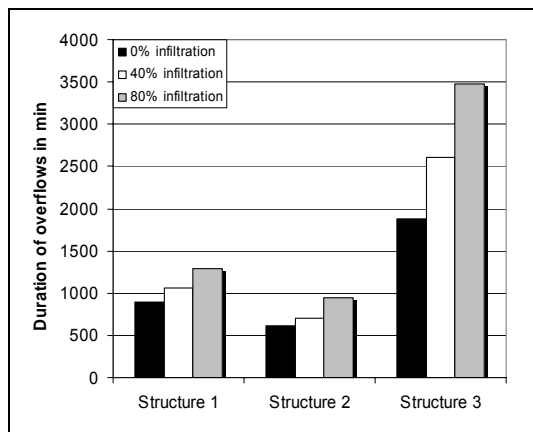


Figure 17: Duration of CSO spills

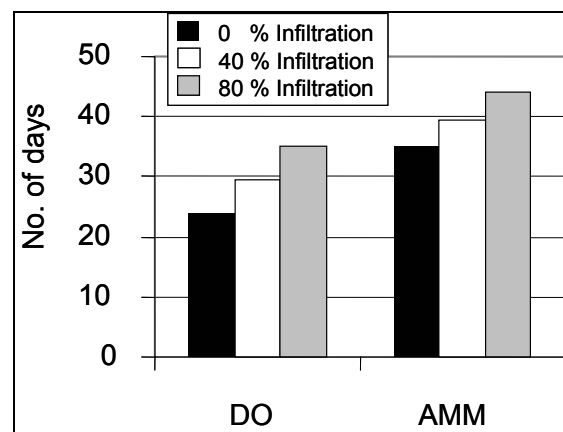


Figure 18: No. of days with critical min oxygen and Ammonium concentration

Furthermore, the study shows that the effects of an increase in the infiltration rate into the system can be estimated by the integrated model. Results then can be related to the costs of avoiding these impacts. In that case, the network deterioration model can be used for the calculation of rehabilitation needs in terms of an annual budget, required for maintaining the present network condition in terms of the percentages of condition grades in the network for certain years in the future.

The objective of the study (Schulz/Baur/Krebs 2004) was the estimation of potential benefits of sewer pipe rehabilitation for the performance of the drainage system and the wastewater treatment plant (WWTP) as well as for the receiving water quality. The relation of sewer system status and the infiltration rate was assessed based on the statistical analysis of 470 km of CCTV inspected sewers of SEDD, Dresden. Critical pipe types have been identified and it was shown that the potential reduction of infiltration volumes and the consequent performance improvements of the urban wastewater system can be simulated as a function of rehabilitation activities in the network. The integrated model was applied to a virtual system with input from a real sewer network.

Infiltration rates will only decrease significantly if large sewers or large parts of a network are rehabilitated. After rehabilitation the groundwater level may rise or the groundwater will search new pathways to infiltrate into another location (pipe) of the sewer system. If a procedure is available to estimate the infiltration rate before and after rehabilitation, the integrated simulation can deliver indicators to relate the rehabilitation costs to the improvement of the quality of receiving waters. In Germany, concentrations of WWTP effluents are used to monitor the performance. If a violation of the threshold concentration is associated with costs, the lower pollution concentrations in catchments with a higher infiltration rate could even be an advantage, and thus it could be an argument *against* rehabilitation measures although the operational costs in the WWTP might increase and higher pollution loads are discharged. Therefore, the definition of criteria used in the assessment of infiltration effects is a very important issue that should be handled carefully.

The application of an integrated model for the evaluation of rehabilitation including infiltration effects is only useful if sufficient data is available in all compartments of the system and if a method can be applied to estimate the infiltration as a function of the condition state of the sewer system. Both requirements are not fulfilled completely until now. Within the study, so far, infiltration volumes were subject to parametric variations in the integrated model, and the effects of different infiltration rates on the urban water system were simulated, e.g. in terms of CSO volumes and frequencies. By the deterioration model the length of pipes that will enter worse condition grades within a defined forecast horizon can be calculated. Even if there is not a causal connection between condition grade and infiltration volumes, such a factor could be a suitable input parameter for the integrated model and for estimating the efficiency of a strategy.

Choosing the right strategy

The best or most robust strategy for sewer rehabilitation can not easily be found by a formalised procedure, like it has been proposed for the rehabilitation strategies of drinking water networks in CARE-W (Herz et al. 2003). The number of predictable technical indicators which can be compared to associated investment costs is limited to the structural condition grade. Hydraulic or operational rehabilitation of the networks and the associated costs can be evaluated. However as be seen for the example given above on infiltration into the network, the expected benefits of such a rehabilitation programme are not predictable with sufficient accuracy by the existing tools.

In general, choosing a rehabilitation strategy is a ranking problem, and therefore the formalised balancing and ranking procedure presented by Strassert (1984) is an appropriate approach. The results delivered by CARE-S SRS give some pros and cons for a structured balancing process. However, in the development of a long-term strategy specific local conditions and problems may play such an important role, that a very restricting framework, for instance provided by a computer software, for the ranking of alternative strategies does not seem to be an adequate solution of the problem. So, the results of CARE-S SRS provide the end-user with a strategic budget planning tool that considers the development of the structural condition of the network. Additional criteria, however, must be provided by external studies and long-term simulations of the network performance.

4 Priority setting

In general, the total cost of all viable rehabilitation projects exceed the available budget, thus not all sewers in critical condition can be rehabilitated immediately, and it becomes necessary to select those rehabilitation projects promising highest cost efficiency.

Interactive Elimination Procedure (IEP)

The IEP is a procedure that frequently exists in a non-formalised variant in many fields of technical and political decision making where public is involved. A typical example is urban planning, where the candidates are elaborated within a competition, and a jury is setting the thresholds for the elimination of candidates that are not good enough. Then, some candidates may be better in design, others in functionality, and a third group is cheaper. It's up to the jury to set the threshold for costs, and to check what functionality and design is still affordable. If they agree, the threshold is accepted, and the set of candidates is eliminated, until a final solution, or set of drafts for a more detailed planning, is selected. The objective of the engineer is the appropriate presentation of information and criteria, in order to illustrate the required trade-offs of a decision. This decision methodology can be characterised as feasibility and sensitivity analysis by attributes or criteria. It aims to control the effect of the performance of other criteria, if for one criterion an elimination threshold is set for rehabilitation projects that are "not so good" (Gero 1982, Hochstrate 1986, Baur 2003).

In the schematic outline of Figure 19 the procedure is demonstrated for 4 criteria: a first elimination threshold (1) is set for criterion C1. This leads to the elimination of a certain number of projects (grey dashed areas). The consequences of the elimination of these projects does not consequently reduce the performance range of the other criteria on the less efficient side: due to the elimination of pipes with a lower failure risk possibly those pipes that probably cause major quality problems in the network would be eliminated. Therefore, elimination thresholds must be accepted or not (or modified (2)) after an effect control of the respective elimination. Once an elimination step is confirmed, the next threshold is set at another criterion (3). By this procedure step by step those projects for rehabilitation are eliminated that promise less cost efficiency than the others. The process comes to an end, when the break-off limit is reached, which could be, for example, a budget limit or a certain rehabilitation rate.

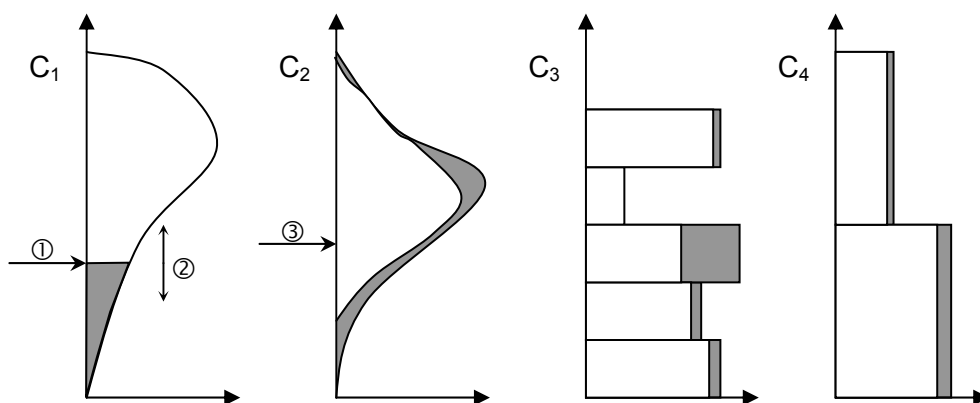


Figure 19: Schematic outline of the interactive elimination with effect control (Baur 2003)

The order, in which the criteria are chosen for the elimination steps, is free. Mathematically, the result will not be influenced by the order, due to the conjunctive nature of the thresholds (mathematically, the elimination conditions are joined by a logical OR) (Zimmermann and Gutsche 1990). However, different preferences might be expressed by the decision maker, in the case of a changing order of decision criteria. In practice, the elimination will start with "hard" criteria, for which the decision is not so difficult, and where just minor trade-offs must be accepted, for example for younger pipes of new materials with failure rates under the

network mean. As the decision process advances, more and more “softer” decision criteria will be applied: e.g. the presence of sensitive customers or complaints. This way, the decision maker’s understanding of the consequences of his decisions and the possible trade-offs will be improved step-by-step (Hochstrate 1986).

Threshold setting and criteria presentation

For supporting a reasonable threshold setting, different presentation tools are applied and developed for use in the elimination process: tables, charts, histograms and cumulative curves are combined with a map for the spatial presentation of the selected projects (Baur 2003, Kropp and Baur 2002). By the different tools and the map, the remaining projects, as well as the eliminated projects can be presented. Thus, a permanent control of the elimination process is possible.

Thresholds are preferably chosen with the aid of sensitivity curves, which show the relative distribution of criteria. This way, potential gaps that would be appropriate for a threshold setting can be more easily identified. In Figure 20 one of these gaps can be observed for the failure rate of service pipes in the remaining set of potential rehabilitation projects between 2.3 and 2.6 failures per km of distribution pipe and year. For the subsequent effect control, absolute distribution curves are used. In the example of Figure 21 the reduction in the distribution of the diameter is shown after the elimination of all pipe sections for which no failures are recorded to date. Additionally, elimination steps are documented on a network map (Figure 22).

Service pipe failures/km*year

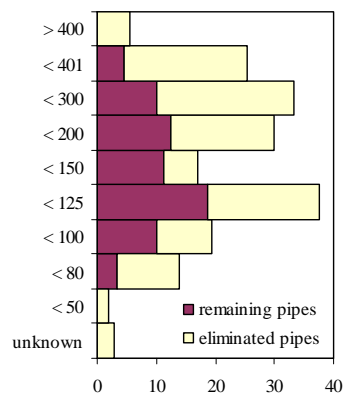
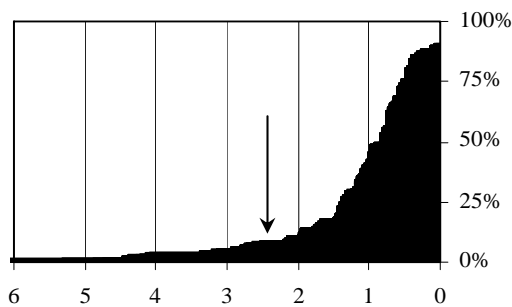


Figure 20: Sensitivity curve for failure rate of service pipes

Figure 21: Effect control with distribution curve for remaining and eliminated length of pipes by diameter

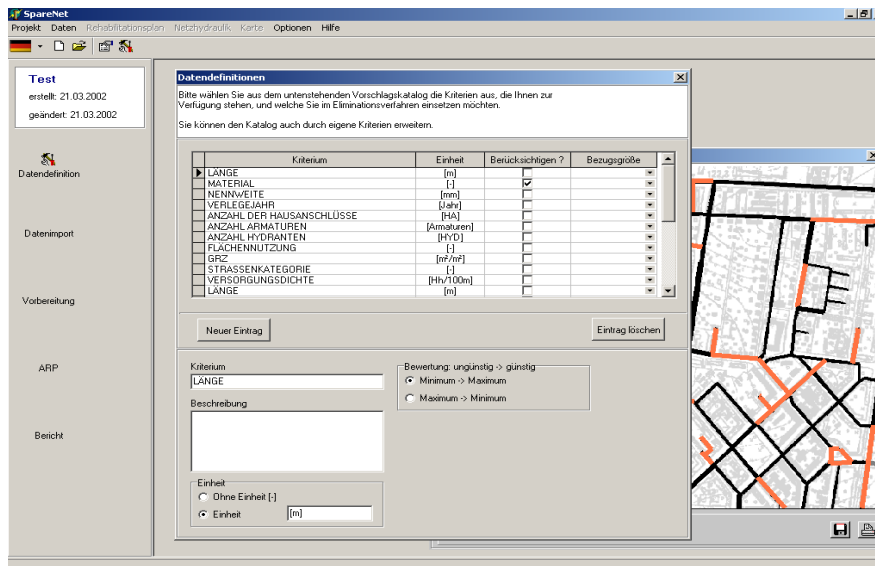


Figure 22: Application screen for the interactive elimination procedure (Kropp and Baur 2002)

Formalisation of the procedure

The interactive elimination procedure for the selection of efficient pipeline rehabilitation projects is given a formal structure that is outlined in Figure 23. The procedure starts with the preparation and organisation of existing information and the development of the decision matrix. In the decision matrix, potential rehabilitation projects must be clearly identified entities that are associated with their performance at different criteria. Then, a break-off limit must be defined. It is advisable to define the reference solution at certain decision criteria, from which an individual effect control is carried out, with the cumulative curves of the respective criteria. The reference values can be modified during the elimination procedure without any direct influence on the final solution.

A first elimination threshold is set for an attribute that allows without many difficulties the elimination of the projects. Hence, the elimination threshold should not be too rigid. The affected pipes are marked and, temporarily, eliminated from the final solution. In the case of projects that will be definitely selected for the rehabilitation plan, for example due to co-ordination with road works, these projects can be labelled as “finally selected”.

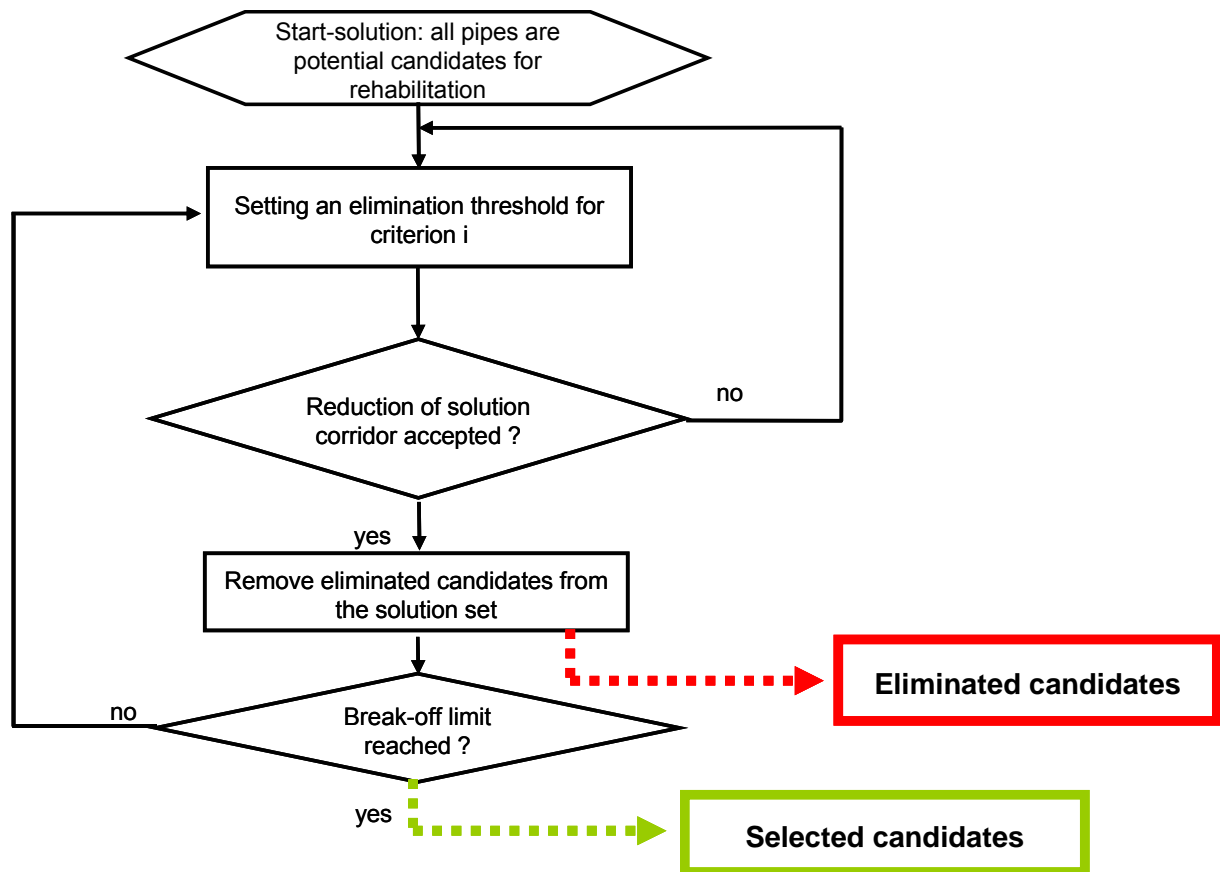


Figure 23: Interactive elimination procedure, flow chart

After the temporary elimination of pipes by the first elimination criterion, the effects of this elimination must be controlled. An overview of the selected pipes gives the map, the changes in the criteria performances can be observed by the histograms, charts or cumulative curves. If any projects exceed one of the reference values, the elimination must be confirmed individually. If the reductions of the criteria performances are accepted, and if no eliminated project exceeds for any criterion its reference value, the elimination is confirmed and the projects are finally eliminated. Now the decision maker can decide, whether to increase the threshold for the first elimination criterion, or to choose another criterion, for which a new threshold is set. If the restrictions and trade-offs after the elimination can not be accepted, the threshold must be modified.

Then the next elimination criterion is chosen, and the procedure continues until the break-off limit is reached. When the procedure comes to its end, not necessarily all criteria have been used for elimination. In fact, there will be some criteria that preferably might be used just as “control-criteria” by the decision maker, whereas others are mainly used for the active threshold setting.

In order to avoid unacceptable or undesired eliminations, warning limits can be set for criteria that will not be chosen for threshold setting in the first place. These limits are so-called reference thresholds.

If in the decision maker's opinion no further trade-offs could be accepted before the break-off limit is reached, new alternatives must be developed (for example by the selection of low-cost techniques), the constraints must be changed (for example by increasing the budget), or the information base must be improved, in order to have better chances to set priorities between the projects. Each elimination step is documented in a protocol with the thresholds, the modifications and the confirmation status (yes/no) set. Within the protocol the argumentation for the acceptance of trade-offs can be reported, and the voting behaviour in majority decisions is documented, as well.

The result of the procedure is presented in lists and maps, and it includes the minutes of the decision process. The procedure will not necessarily converge to results in the sense of a mathematical optimum, but it will give a better understanding of the problem (with respect to data availability and requirements) and it will stimulate a learning process, which should be the objective of any method of decision-support.

Application

Criteria for the selection of rehabilitation projects in a sewer network are the different classification results and priorities with respect to structural and hydraulic aspects, environmental aspects and the associated direct and indirect costs. External effects are considered by the risk associated with the deficiency of the sewers, for example the potential damage due to frequent flooding or the potential groundwater pollution due to an exfiltrating sewer. Supported by a geographical presentation of the network (Figure 24), the candidates for rehabilitation are selected, step-by-step, in an interactive elimination process. Within the procedure which was successfully applied to the rehabilitation planning of water distribution networks, those candidates are eliminated which are not fulfilling specified thresholds. The remaining candidates have a bundle of attributes favourable for rehabilitation (Baur 2003).

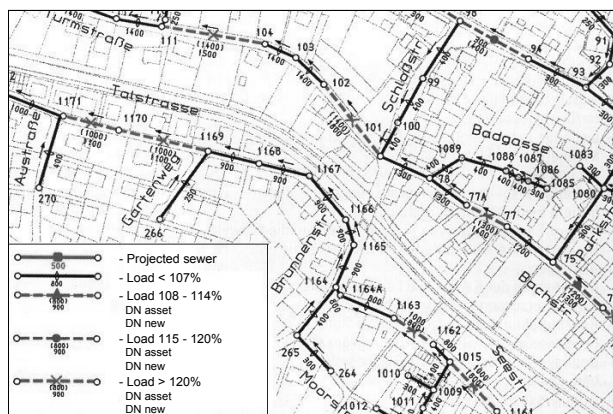


Figure 24: Rehabilitation priorities in a network due to hydraulic loads (MUV-BW 2000)

The interactive elimination process has been developed for the rehabilitation of infrastructure networks, and modified for the development of sewer network rehabilitation plans in CARE-S. Alternatively, the concordance analysis developed for CARE-W (Le Gauffre et al. 2002b), has been subject to investigations within CARE-S.

Decision criteria for the setting of priorities consider the actual hydraulic (functional) and structural condition of the pipes and the potential impacts in the case of malfunction. Within CARE-S, decision criteria are the condition grade, and those defined by WP3 (Hellmud tool) and WP5 (socio economic evaluation). The tool for priority setting does not require a completely filled table with values for all pipes at all criteria, but can deal with “unknown” fields.

CARE-S SRT requires for each pipe at least an ID, the pipe length (or default length) and default unit costs for rehabilitation for a rough estimate of the total rehabilitation costs. The benefit of the application of CARE-S SRP increases with the number of criteria values provided.

The fields for criteria correspond to the criteria developed by other WP in CARE-S. The import data table consists of the following columns:

- PipeID
- ManholeID Upstream
- ManholeID Downstream
- Street
- Sewer type
- Installation year
- Length
- Height
- Width
- Material
- Depth
- Condition grade (from inspection, or WP2)
- Filling level (WP3)
- Flow velocity (WP3)
- Material damage and loss of trade (WP5)
- Intangible damage to population (flooding) (WP5)
- Road/traffic disturbance (flooding) (WP5)
- Service interruptions due to blockages/chokes (Quality of life) (WP5)
- Soil depression due to sewer collapse(WP5)
- Wastewater flooding in the basements (during dry weather) (WP5)
- Wastewater flooding on the street surface (during dry weather) (WP5)
- Odours, rodents and insects due to collapse or blockage (WP5)
- Pollution of receiving waters by overflow (WP5)
- Pollution of groundwater resource by exfiltration (WP5)

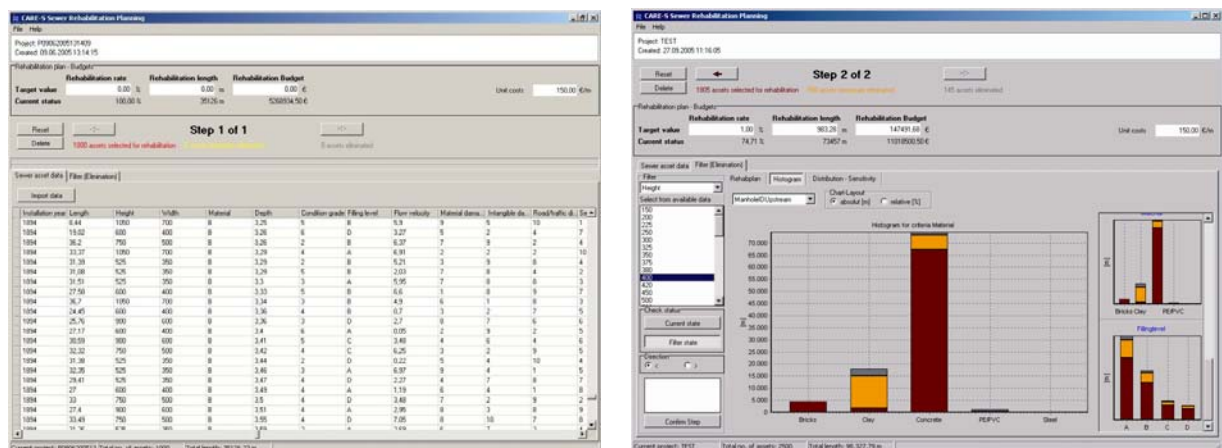


Figure 25: Interactive elimination procedure, application screens

The consideration of criteria, and consequently the definition of priorities depend highly on the local “rehabilitation philosophy”. In Germany, where the wastewater companies are legally obliged to optically inspect their total networks frequently, the decision for priorities is mainly based on inspection results and their interpretation. The condition forecast of single pipes or sewer types, therefore is rather used for planning and scheduling inspection, and for the long-term budget planning.

During the preparation of a comprehensive data set for the Dresden case study, data hunger, respectively the time consuming data acquisition, of the evaluation of criteria defined by WP 5 (socio-economic aspects) became a major obstacle. In many cases, companies may use substituting criteria, such as simply the traffic density, street category, or land use type of a certain area. In principle, the CARE-S user has no constraints in the definition of data inputs

for criteria; they must not necessarily be calculated by the respective CARE-S tools, as long as the input file structure does not comply with the programme requirements.

Within CARE-S, the intermediate steps cannot directly be displayed on the map. However, direct interaction with the GIS-viewer would support the decision process significantly. The user could for instance tile the CARE-S main screen, save intermediate results, and reload them on the GIS-viewer.

5 Rehabilitation technology

The best rehabilitation technology is chosen according to its suitability at a particular site, and its relative advantages compared to other technologies. Thus, criteria are required for the elimination of unsuitable technologies, and for the comparison of suitable technologies.

Information on rehabilitation technologies is coming from a rehabilitation technology data base developed within working package 4. The description of technical and environmental conditions of a sewer pipe selected for rehabilitation is the basis for the technology evaluation. Additional criteria are calculated by the tool socio-works (working package 5).

The first objective was to compare available information on rehabilitation technologies relative to a description of the project(s) proposed. Information on rehabilitation technologies will come directly (or via the CARE-S rehabilitation manager) from the catalogue established in WP4 by CLABSA. The project description is taken from various sources (WP2, WP3, WP5 and the end-user's data bases) in a pre-defined format via the CARE-S rehabilitation manager.

A survey among the CARE-S end-users was conducted, asking for the documentation of two or three recently finalised rehabilitation projects in their networks. The intention was:

1. To find out which decision criteria are/were used by our end-users for choosing rehabilitated **sewer sections**.
2. To obtain descriptions of applied **rehabilitation technologies** and reasons for the selection.
3. To evaluate the **costs** of the used rehabilitation technology.

Co-operating end-users from 9 countries returned 11 filled questionnaires providing 27 described projects (case studies). The results of the survey give an overview on how presently rehabilitation technologies are selected; the majority of the case studies are examples of the application of trenchless technologies (Figure 26). For detailed survey results see Baur et al. (2003c).

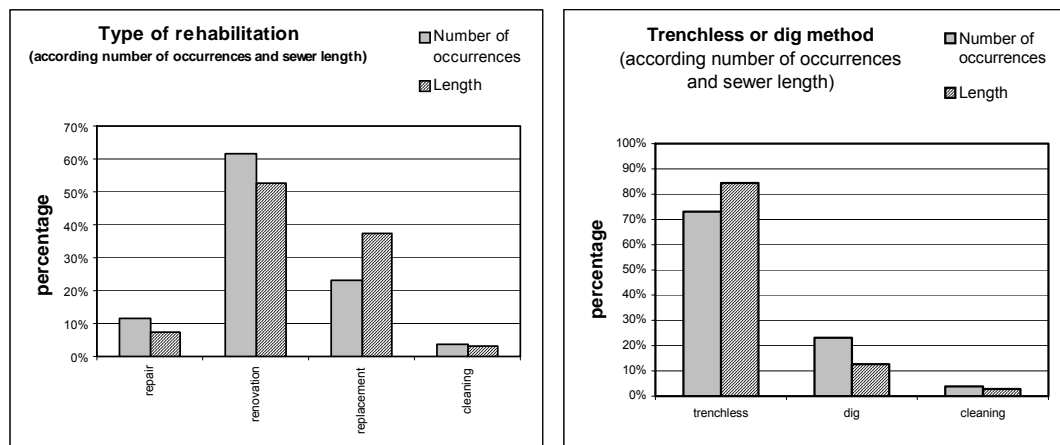


Figure 26: Type and method of rehabilitation for the 27 case studies

The approach chosen for ranking rehabilitation technologies is the formalised balancing and ranking procedure.

Balancing and Ranking procedure

The balancing and ranking procedure presented by Strassert (1984, 1995) and Köhl (1998) is a variant within the field of semi-formalised multi-criteria decision support methodologies. "Basic features of the approach are the pairwise comparisons of options, mixed scales and the so-called balancing principle, i.e. the balancing of vectors of advantages and disadvantages" (Strassert 2000: 1). For any pair of options the relative advantages and disadvantages are balanced and, simultaneously, the different importance of the score is

taken into account. Strassert (2000) gives a detailed derivation and description of the methodology. It has been applied in CARE-W to the evaluation of rehabilitation strategies (Herz et al. 2003), and to the choice of the best rehabilitation technology for sewer pipes (Schmidt 2002).

Preliminary order of candidates

The procedure starts with the impact matrix (Figure 9). Each criterion C_i yields an individual order of candidates P_j by means of e_{ij} . For $e_{11} > e_{12} > e_{13}$, the ranking order of criterion C_1 is P_1, P_2, P_3 . In general, the ranking order of candidates P_j will differ for all criteria C_i .

Now suppose that the values e_{ij} show that, for $C_1, P_1 > P_2 > P_3$. Then we can write:

$C_1: < P_1, P_2, P_3 >$, and similarly for C_2 and C_3 , for example

$C_2: < P_3, P_2, P_1 >$,

$C_3: < P_3, P_1, P_2 >$,

In an “outranking matrix” (Figure 27a), the number of pros and cons are counted for each candidate. The matrix in Figure 27a shows that candidate P_1 is placed twice (i.e. for two criteria) before candidate P_2 , once before P_3 , and vice versa P_2 is placed once before candidate P_1 , and P_3 is placed twice before candidate P_1 (The tables must be read in rows).

| | | | |
|-------|-------|-------|-------|
| | P_1 | P_2 | P_3 |
| P_1 | 0 | 2 | 1 |
| P_2 | 1 | 0 | 1 |
| P_3 | 2 | 2 | 0 |

Figure 27a: Outranking matrix

| | | | |
|-------|-------|-------|-------|
| | P_3 | P_1 | P_2 |
| P_3 | * | 2 | 2 |
| P_1 | 1 | * | 2 |
| P_2 | 1 | 1 | * |

Figure 27b: Triangular outranking matrix

When the “outranking matrix” is set up, the options must be re-ordered to achieve a triangular matrix (Figure 27b). Triangularisation is the systematic re-ordering of candidates such that out of a set of $p = j!$ orders, the sum of the values above the main diagonal is maximised. A situation where only zero values are below the main diagonal corresponds to a strong transitive overall final order of candidates, or total order structure. Normally, this total order structure of candidates does not exist initially (Vincke 1992, Strassert 2000).

The outranking matrix relates to the majority rule of counting votes (1 criterion \rightarrow 1 vote). In the context of the balancing principle, the assumption of a majority rule must be given up. The outranking matrix is used instead as a preliminary order of candidates which is then subject to a screening and balancing process.

The balancing process

Firstly, a new table is introduced. In an “advantages-disadvantages table” the criteria C_i are combined with the result of the pair wise comparison of candidates P_j/P_k (Figure 28). The column headings contain all possible comparisons in pairs. For n candidates the number of comparisons is $z = n*(n-1)/2$. In our case ($n = 3$), $z = 3$.

| | | | |
|--------------|--------------|--------------|--------------|
| | P_1/P_2 | P_1/P_3 | P_2/P_3 |
| C_1 | $A_{P_1C_1}$ | $A_{P_1C_1}$ | $A_{P_2C_1}$ |
| C_2 | $D_{P_1C_2}$ | $D_{P_1C_2}$ | $A_{P_2C_2}$ |
| C_3 | $A_{P_1C_3}$ | $D_{P_1C_3}$ | $D_{P_2C_3}$ |
| ΣA_j | 2 | 1 | 2 |
| ΣD_j | 1 | 2 | 1 |

Figure 28: Advantages-disadvantages table

For each comparison in pairs, the scores of e_{ij} must be compared. The comparisons can be made independently from the criteria's scales. They refer to quantities, rankings or frequencies (cardinal, ordinal, nominal scale). At the bottom of the table two rows show the sum of advantages ΣA_j and the sum of disadvantages ΣD_j by comparison.

In the advantages-disadvantages table, each column represents a separate binary decision problem: in the first column, the comparison P_1/P_2 of the two candidates P_1 and P_2 , the question is whether the two advantages $[_{1/2}A_1, _{1/2}A_3]$ together are strictly superior (or not) to the disadvantage $_{1/2}D_2$. For "Yes", P_1 is strictly superior to P_2 . If respectively the answer is "No", then P_2 is strictly superior to P_1 . If the answer to the question: Are $[A_{P_1C_1}, A_{P_1C_3}]$ strictly superior to $D_{P_1C_2}$ is "Yes", the disadvantage $_{1/2}D_2$ loses its importance.

Thus, each comparison result is rated according to a boolean code (1,0), and the results of all comparisons can be drawn to a compatibility matrix C (Figure 29a), and if the compatibility matrix is reordered, to the triangular compatibility matrix C^T (Figure 29b).

| | P_1 | P_2 | P_3 |
|-------|-------|-------|-------|
| P_1 | 0 | 1 | 1 |
| P_2 | 0 | 0 | 0 |
| P_3 | 0 | 1 | 0 |

Figure 29a: Compatibility matrix C

| | P_1 | P_3 | P_2 |
|-------|-------|-------|-------|
| P_1 | 0 | 1 | 1 |
| P_3 | 0 | 0 | 1 |
| P_2 | 0 | 0 | 0 |

Figure 29b: Triangular compatibility matrix C^T

The triangular compatibility matrix C^T is representing a "strict total order" with a binary relation, which is asymmetric, complete and transitive (Vincke 1992). With this matrix, the overall final order of candidates looked for is obtained, i.e. $\langle P_1, P_3, P_2 \rangle$ (Strassert 2000).

Operating comparisons in pairs

In practice, the number of candidates, e.g. rehabilitation technologies, to be compared can easily be 5, 6 or more. Then the number of comparisons in pairs z is 10, 15, or more, respectively. Irrespective the number of criteria, the determination of the order relations could become a clumsy job.

Not necessarily all possible comparisons in pairs and corresponding balancing problems must be carried out. For 4 strategies, the number of comparisons would be 10. The number of possible orders of candidates is $p = n! = 1*2*3*4 = 24$. These orders are:

- | | | | |
|----------------------|----------------------|----------------------|----------------------|
| P_1, P_2, P_3, P_4 | P_2, P_1, P_3, P_4 | P_3, P_1, P_2, P_4 | P_4, P_1, P_2, P_3 |
| P_1, P_2, P_4, P_3 | P_2, P_1, P_4, P_3 | P_3, P_1, P_4, P_2 | P_4, P_1, P_3, P_2 |
| P_1, P_3, P_2, P_4 | P_2, P_3, P_1, P_4 | P_3, P_2, P_1, P_4 | P_4, P_2, P_1, P_1 |
| P_1, P_3, P_4, P_2 | P_2, P_3, P_4, P_1 | P_3, P_2, P_4, P_1 | P_4, P_2, P_3, P_3 |
| P_1, P_4, P_2, P_3 | P_2, P_4, P_1, P_3 | P_3, P_4, P_1, P_2 | P_4, P_3, P_1, P_2 |
| P_1, P_4, P_3, P_2 | P_2, P_4, P_3, P_1 | P_3, P_4, P_2, P_1 | P_4, P_3, P_2, P_1 |

If $n - 1$ comparisons in pairs are already executed, and if all candidates are considered in the balancing process, the remaining comparisons are given implicitly. For example, if $n - 1 = 3$ comparisons yield the three orders $\langle P_1, P_2 \rangle$, $\langle P_1, P_4 \rangle$ and $\langle P_3, P_2 \rangle$, then from the 24 orders above, in a first step 12 are eliminated (all orders where P_1 is before P_2), in a second step 8, and in a third step 3 orders are eliminated, respectively. Hence, only one single order, $\langle P_1, P_4, P_3, P_2 \rangle$, remains, that is the final order of candidates.

Intransitivities occur when the balancing result of three comparisons would give rankings of the form: $\langle P_1, P_2 \rangle$, $\langle P_2, P_3 \rangle$ and $\langle P_3, P_1 \rangle$, i.e. the circular relation $P_1 > P_2 > P_3 > P_1$. Strassert (1999) gives an analytic proof that the number of comparisons in pairs could be reduced down to a minimum of $n-1$ comparisons, and a methodology how to avoid intransitivities in the final order. For the pre-elimination of candidates, knockout criteria are introduced (e.g. applicability conditions).

Solving balancing problems

The solution of the balancing problem is the comparison of two candidates with respect to the set of advantages against the set of disadvantages, presented in the “advantages-disadvantages table”. That is the answer to the question: Are the advantages $[\frac{1}{2}A_1, \frac{1}{2}A_3]$ strictly superior to the disadvantage $\frac{1}{2}D_2$?

The number of criteria in each comparison with an equal score is not decisive. A dominance check looks for comparisons, where we have only advantages but no disadvantages. Rankings including the inverse of such a dominance order can be removed from the set of possible rankings.

Example application of BRP

In Table 2, the impact matrix of 4 options and 4 criteria is shown. In the example the knockout-criterion is a maximum of 250€/m for the costs. Thus, option D would be excluded from the set of available options.

Table 2: Impact matrix e_{ij}

| Criteria i | Options j | | | |
|------------------------------------|-----------|-----------|----------|-----------|
| | A | B | C | D |
| K ₁ Costs | 150 €/m | 200 €/m | 50 €/m | 300 €/m |
| K ₂ Construction time | 5 weeks | 10 weeks | 20 weeks | 30 weeks |
| K ₃ Traffic disturbance | medium | very high | low | none |
| K ₄ Service life | 50 years | 50 years | 80 years | 120 years |

Subsequently, for each criterion a rank will be assigned to the remaining options. If there are equal criteria values the options get the same rank (Table 3).

Table 3: Ranking of options

| Criteria i | Options j | | Rank A | Rank B | Rank C |
|------------------------------------|-----------|-----------|--------|--------|--------|
| | A | B | | | |
| K ₁ Costs | 150 €/m | 200 €/m | 2. | 3. | 1. |
| K ₂ Construction time | 5 weeks | 10 weeks | 1. | 2. | 3. |
| K ₃ Traffic disturbance | medium | very high | 2. | 3. | 1. |
| K ₄ Service life | 50 years | 50 years | 2. | 2. | 1. |

The dominance test is next. For this purpose, the individual options are compared in pairs using an advantage-disadvantage table. If there is one option in all criteria better than any another, that option will be strictly superior to all others in every possible order of options. In the example option A is strictly superior to B, which means option B will never be before option A in the final ranking. There is no obvious strict superiority in the comparisons A-C and B-C. The advantage-disadvantage table is shown below (Table 4.)

Table 4: Advantage-disadvantage table for the dominance test

| Comparisons Criteria | A-B | A-C | B-C |
|------------------------------------|----------------------|-----------------|-----------------|
| K ₁ Costs | A _{A1} | D _{A1} | D _{B1} |
| K ₂ Construction time | A _{A3} | A _{A3} | A _{B3} |
| K ₃ Traffic disturbance | A _{A4} | D _{A4} | D _{B4} |
| K ₄ Service life | O ₅ | D _{A5} | D _{B5} |
| Result | A dominates B | - | - |

Three possibilities out of six possible ranking orders (ABC, ACB, BAC, BCA, CAB, CBA) can be eliminated because option A dominates option B and thus B never will be ranked before A (BAC, BCA, CBA). Therefore two comparisons remain (A-C, B-C). In this example there are no intransitivities (table 4, table 5). Criteria where the compared options have the same value are not be taken into consideration.

Table 5: Pairwise comparison A-C

| Criteria | A | | C | |
|------------------------------------|---|-------------|----------|-------------|
| K ₂ Construction time | 5 weeks | Advantage A | 20 weeks | |
| K ₁ Costs | 150 €/m | | 50 €/m | Advantage C |
| K ₃ Traffic disturbance | Medium | | Low | Advantage C |
| K ₄ Service life | 50 years | | 80 years | Advantage C |
| Result | C is better than A, because the advantages of longer service at 1/3 of costs prevail the disadvantage of longer construction time, which causes only low traffic disturbances | | | |

Table 6: Pairwise comparison B-C

| Criteria | B | | C | |
|------------------------------------|---|-------------|----------|-------------|
| K ₃ Construction time | 10 weeks | Advantage B | 20 weeks | |
| K ₁ Costs | 200 €/m | | 50 €/m | Advantage C |
| K ₄ Traffic disturbance | Very high | | Low | Advantage C |
| K ₅ Service life | 50 years | | 80 years | Advantage C |
| Result | C is better than B, Because the three advantages (costs, service life, low traffic disturbances) prevail the relative small disadvantage of a longer construction time (there are no time constraints here) | | | |

At the end, the final ranking can be stated, in this example it is CAB. The procedure has been finished.

The procedure results (“C is better than A” and “C is better than B”) are decisions, that must be made by the user, including the reporting of the argumentation. The automatically performed check for intransitivities avoids inconsistent preferences, and thus subjective decisions.

Application

Rehabilitation technologies

Information on the new technologies is coming from the data base of rehabilitation technologies (WP4). Operational solutions for the rehabilitation of the sewer network are integrated into the catalogue of rehabilitation technologies. The options for hydraulic rehabilitation are the result of the hydraulic analysis in WP3. In Table 7, information stored in the rehabilitation technology database (WP4) is set in relation to requested information for the description of the projects.

Cost evaluation

In general, cost evaluation should give an economic justification of the rehabilitation decision. Different options should be compared with respect to the ratio between costs and service life prolongation for repair, and depreciation plus interest for renovation and replacement respectively. According to the three fields of interest in the decision framework for sewer network rehabilitation, costing approaches with different levels of detail must be included into the decision process. The cost-factor matrix is a spreadsheet developed by CLABSA under WP4, a detailed description is given in (CLABSA 2005).

The choice of the right rehabilitation technology requires very detailed cost estimates, potentially already taken from different previous bids. For the prioritisation of projects, estimates of mean costs for different rehabilitation technologies under specific conditions may be adequate. For the development of long-term strategies for inspection and rehabilitation, unit costs for inspection and mean costs for different rehabilitation technologies should be available.

Software design

Beside typical data management facilities, the general design of the CARE-S – SRT software consists of two main screens. The first one provides information on the rehabilitation project, including pipe characteristics, failure specification, and description of the environment (Figure 6.22). Here, the pre-selection of suitable technologies is carried out.

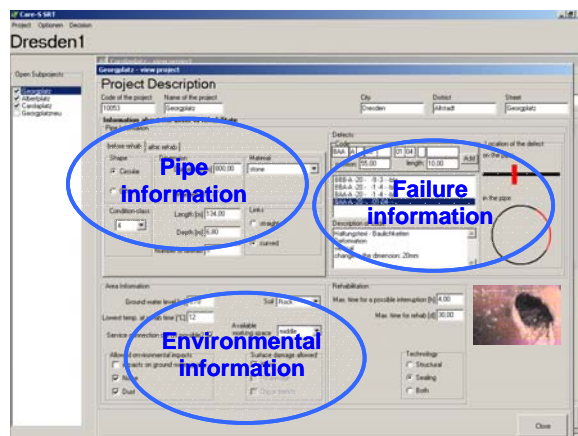


Figure 30: Project description

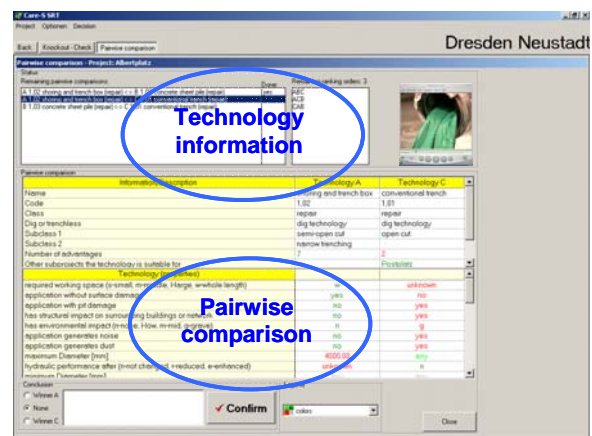


Figure 31: Ranking

On the second screen, the remaining rehabilitation technologies are listed with their advantages and disadvantages, and the ranking process is carried out (Figure 6.23). A more detailed description of the software is included in the software handbook.

Table 7: Information on rehabilitation technology and project description

| | Information on the rehabilitation technology | Project description |
|----|--|---|
| | Applicability conditions | |
| 1 | Diameter (min, max) | Diameter (before, after rehabilitation) |
| 2 | Shape (circular, non-circular, man-entry, non-man-entry) | Shape (circular, egg-shaped, other non-circular) |
| 3 | Asset type (sewer, manhole, connection) | Sewer/Manhole/Service connection |
| 4 | Static function (structural, sealing) | Restoration of load bearing capacity required (Yes/No) |
| 5 | Suitable material of current asset | Material |
| 6 | Need to cut off service connections | Number of service connections |
| 7 | Under groundwater level/leakage admissible | Groundwater level, sewer level, Sensitive to groundwater quality? |
| 8 | Minimum temperature | |
| 9 | Suitable kind of soil | Soil type |
| 10 | Working space required | Availability of working space in the urban environment of the sewer |
| | Technology performance / characteristics | |
| 11 | Maximum length | Length |
| 12 | Working speed (length/units per day) | Time constraints (max d) |
| 13 | New asset material | Material |
| 14 | Diameter after rehabilitation (not changed, reduced, increased) | New diameter |
| 15 | Hydraulic performance after rehabilitation (diameter, slope, roughness: not changed, reduced, increased) | New diameter, new slope, new roughness, Failure type |

| | | |
|----|---|---|
| 16 | Digging needs (without surface damage, pit damage, trench) | Availability of working space in the urban environment of the sewer, Number of service connections, Traffic load in the location, Existing flora to be protected? Sensitive buildings or infrastructure around? Noise and tremor a problem? Business activities affected? |
| 17 | Processing through manhole? | Availability of working space in the urban environment of the sewer |
| 18 | Need of cleansing | |
| 19 | Digging need for connections reinstall | Number of service connections |
| 20 | Possibility of work interruption | |
| 21 | Excess ground permeability during grouting | Sensitive to groundwater quality |
| 22 | Requires man in underground | |
| 23 | Straight/curved link | |
| 24 | Estimated service life (prolongation) of rehabilitated asset | |
| 25 | <i>Unit costs and cost factors (not yet included in CLABSA table)</i> | |
| | Environmental impact | |
| 26 | Structural impact on surrounding buildings | Sensitive buildings or infrastructure around? |
| 27 | Environmental impact (material, works: none, low, grave) | Existing flora to be protected? Sensitive to groundwater quality? Noise and tremor a problem? |
| 28 | Impact on groundwater quality | Sensitive to groundwater quality? |
| 29 | Noise | Noise and tremor a problem? |
| 30 | Dust | Dust a problem? |

6 Summary and outlook

Within working package 6 of CARE-S, three tools for decision support in the rehabilitation management of sewer networks have been developed: CARE-S SRS (sewer rehabilitation strategy), CARE-S SRP (sewer rehabilitation priorities), and CARE-S SRT (sewer rehabilitation technologies). The procedures cover the whole range of decisions to be made by a sewer company within its rehabilitation management: from the development of long-term strategies and budget planning, over priority setting for the allocation of the defined budget, to the final decision upon the most appropriate rehabilitation technology for a defect pipe.

The procedures are using information and results, which are produced by other working packages of CARE-S: CARE-S SRS uses results from and interacts with the Gompitz tool for structural deterioration forecasts; CARE-S SRP can use any kind of results produced by other tools, and combine these results with external information, for achieving appropriate decision criteria for priority setting. CARE-S SRT uses the selection results of CARE-S SRP, and the rehabilitation technology data base developed within working package 4.

Working package 6 provides the user with tools that bring together the analytical results from other WP tools, and facilitates the analysis of trade-offs and synergy effects within the rehabilitation decision process. However, the results show additional potential for future work: CARE-S SRT is a complete tool which requires just an update of the underlying data base of rehabilitation technologies, from time to time. CARE-S SRP could be improved significantly by a direct link to the GIS viewer, in particular for the possibility of grouping neighbouring pipes of different priority to a joint rehabilitation project. Finally, the CARE-S SRS procedure could be extended into a tool for the calculation and forecast of the capital asset value, depreciation costs, and wastewater tariffs.

This report refers to the methodological background of the three procedures. For practical purpose, for all three tools, hand books and how-to guidelines have been developed.

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Appendix 1

Condition grading

TU Dresden

CARE – S

**Computer Aided REhabilitation of Sewer networks.
Decision Support Tools for Sustainable Sewer Network Management**

WP6 – Multicriterion Decision Support

Condition grading (Germany)

Principles

Computerised condition grading schemes are the basis for the ageing forecast. In this Appendix, systems are presented that turn defect codes into calculated internal condition grades. Most systems are grading the sewers in order of severity. If this type of grading is appropriate to statistical deterioration models, is discussed controversially (Hochstrate 2000).

In Germany, classification models translate inspection codes into condition grades, mainly into priorities with respect to the most severe defect (Stein 1998). According to EN 752-5, condition of sewers is evaluated with respect to structural and hydraulic defects, and environmental aspects.

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Condition classification

In the first step, inspection results are classified by the most severe defect of the pipe into a preliminary ranking order. The ranking order is defined by five condition classes. Condition class 0 requires immediately rehabilitation activities, whereas condition class 4 means no need of action.

Condition points are assigned to the condition classes (Table 8). The amount of condition points can be adjusted by the engineer, depending on the position and density of the defects.

Table 8: Condition class and condition points

| Condition class | Condition points |
|------------------------|-------------------------|
| 1 | 301 – 400 |
| 2 | 201 – 300 |
| 3 | 101 – 200 |

Condition evaluation

Evaluation factors are used for weighting hydraulic aspects (H) and environmental relevance (Q – for the quality of the fowl water) of the defects. The evaluation factor is an aggravating factor for H and Q and must be chosen between 1 and 1.3 (1.0; 1.1; 1.2; 1.3).

Once the evaluation factors are determined the evaluation points of a pipe are calculated by:

$$BP = ZP + 100 * Q * H + 200 + 69 * [INT (ZP-1)/100 - 1]$$

BP: evaluation points

ZP: condition points

Q: evaluation factor quality

H: evaluation factor hydraulics

INT: Integer – function for eliminating decimal places

Evaluation points are calculated for only sewer pipes where exfiltration is a problem:

Table 9: Evaluation points and condition class

| Evaluation points | Condition class |
|--------------------------|------------------------|
| 739 – 907 | 1 |
| 570 – 738 | 2 |

| | |
|-----------|---|
| 401 – 569 | 3 |
|-----------|---|

For sewer pipes with infiltration, the formula for calculating evaluation points is not applied, because infiltration may only have an influence on structural stability and operational results. Here, the condition points are directly transformed into evaluation points. After the calculation of the evaluation points, the evaluation number is calculated by:

$$BZ = ZK_f * 10^5 + KA_f * 10^4 + SR_f * 10^3 + BP$$

- BZ:* Evaluation number
- ZK_f:* Condition class factor
- KA_f:* Sewer type factor
- SR_f:* Protection factor
- BP:* Evaluation points

The calculation of the evaluation number considers sewer type, and the type of protection zone:

| Condition class | ZK_f |
|------------------------|-----------------------|
| 1 | 3 |
| 2 | 2 |
| 3 | 1 |

| Sewer type | Ka_f |
|-------------------|-----------------------|
| Fowl or combined | 5 |
| stormwater | 2 |

| Protection | SR_f |
|----------------------------|-----------------------|
| Water protection zone IIIa | 5 |
| Water protection zone IIIb | 4 |
| Other water rights | 3 |
| Other exfiltration | 2 |
| Infiltration | 1 |
| Operation | 0 |

Result is a 6 digits number. The 6 positions indicate: 1. the actual condition class, sewer type, 3. Protection zone 4., 5., and 6. position indicates evaluation and condition points, and the final condition grade. The possible evaluation numbers' range is from 355.907 to 120.401.

A final ranking order of priority pipes is found by the ranking order of the evaluation numbers. It is obvious that the methodology is complicated and not very transparent. Therefore it is not widely applied, but a large number of local systems were developed, and also industry provides professional classification schemes. Examples are:

KAIN

ISYBAU

Pforzheim model

Bietigheim model

The German end-user in CARE-S is Stadtentwässerung Dresden (SEDD), where another local classification scheme is applied.

Dresden

The Dresden classification scheme is based on a scoring model that considers mainly the result of the optical inspection of the sewer. First, defect intensity grades (DIG 1-5) are

assigned to defect pipes, where the severest defect is responsible for the grade:

| DIG | Defect |
|-----|--------------------|
| 5 | Very sever defects |
| 4 | |
| 3 | |
| 2 | |
| 1 | No defect detected |

Due to the different types of defects, an additional evaluation factor (EF 1 – 10) for different types of defects is applied:

| EF | Description |
|----|---|
| 10 | Total collapse |
| 9 | Stability/Function endangered |
| 8 | Large degree of destruction, stability/function still ensured |
| 7 | ... |
| 6 | ... |
| 5 | ... |
| 4 | ... |
| 3 | ... |
| 2 | ... |
| 1 | Perfect condition |

Separately for single defects (SF) and the total pipe length (TP), the defect class DC is calculated on the basis of DIG and EF.

It is calculated by:

$$DC_{SF} = \frac{\sum(DIG_i \cdot EF_i)}{n} \quad n = \text{number of single defects}$$

$$DC_{TP} = DIG_{GH} \cdot EF_{TP}$$

If more than one defect is detected in a pipe, a mean value is calculated. The combination of DIG and EF, following the above equations, results in another value. The limits for the assignment of pipes to condition classes are set by the model user.

| cc | Calculated DC value |
|----|---------------------|
| 1 | $\geq 32 < 50$ |
| 2 | $\geq 18 < 32$ |
| 3 | $\geq 8 < 18$ |
| 4 | $\geq 2 < 8$ |
| 5 | $0 < 2$ |

In addition, a defect density, ie the number of defects per pipe length is considered. It is the ratio between number of defects and pipe length. The higher this ratio is, the worse is the condition class.

| m/defect | cc _{dd} |
|----------------|------------------|
| $0 \geq 5$ | 1 |
| $> 5 \geq 10$ | 2 |
| $> 10 \geq 15$ | 3 |
| $> 15 \geq 20$ | 4 |
| > 20 | 5 |

Finally, the condition grade of the total sewer pipe is calculated. It is the average mean of condition class of the single defects, the total defect of the pipe, and the defect density

$$cg = \frac{cc_{\text{single}} + cc_{\text{total}} + cc_{\text{dd}}}{3}$$

Priorities are set according to the condition grade, which is a priority class, where condition grade 1 indicates highest rehabilitation priority, and 6 a good as new condition of the pipe.