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CARE-W WP4

D10 – Development of the "Rehab Strategy Manager" software

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COMPUTER AIDED REHABILITATION OF WATER NETWORKS
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CARE – W

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

WP4 - Strategic planning and investment

Report D10
Developing of the “Rehab Strategy Manager” software

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1 Introduction

The CARE-W project is funded by the European Community and aims to develop methods and software that will enable engineers of water undertakings to establish and maintain an effective management of their water supply networks, in short: to rehabilitate the right pipes at the right time. The results shall be disseminated as a manual on Best Management Practice (BMP) for water network rehabilitation.

This project is organised in the following Working Packages (WP):

- WP1: Construction of a control panel of performance indicators for rehabilitation;
- WP2: Description and validation of technical tools;
- WP3: Elaboration of a decision support system for annual rehabilitation programmes;
- WP4: Elaboration of a decision support system for long-term strategic planning and investment;
- WP5: Elaboration of CARE-W prototype;
- WP6: Testing and validation of CARE-W prototype;
- WP7: Dissemination;
- WP8: Project management.

Dresden University of Technology is responsible for WP4, which is divided into three tasks, each one with its specific objective, schedule, deliverable and methodology.

Task 1:

A software platform for developing consistent scenarios, the **Scenario Writer**, supporting the creation of future background scenarios for any particular Water Supply Company and opening its “window of opportunities”. This software allows to create consistent paths into the future. Five points on the time axis cover a time span from yesterday into the far future. Three paths – containing context information for network rehab policies, key factors influencing rehab policy for each point in time – open up a funnel into the future [Herz, Lipkow 2002a].

Task 2:

The **Rehab Strategy Manager** based on Dresden’s *KANEW* software allowing the simulation of long term effects of specific rehab options and alternative programmes. This tool starts from a data base containing information on pipelines, previous failures and rehab activities. With specified rehab activities in the medium (programme) term for types of pipelines, parts of the network or the entire network, their effects on network performance indicators, determined in WP1, are simulated on the long run and transformed into monetary terms (Euro), as far as possible.

Task 3:

A software platform **Rehab Strategy Evaluator** allowing the evaluation of rehab strategy output from the Rehab Strategy Manager and taking into account the background scenarios written by support of the scenario writer. Multiple criteria decision support is provided in order to find “the best and most robust” rehab strategy.

All software packages are stand-alone applications with capabilities of interacting as shown in Figure 1 within the extended *KANEW* framework and with the encompassing CARE-W prototype [Herz, Lipkow 2002b,c].

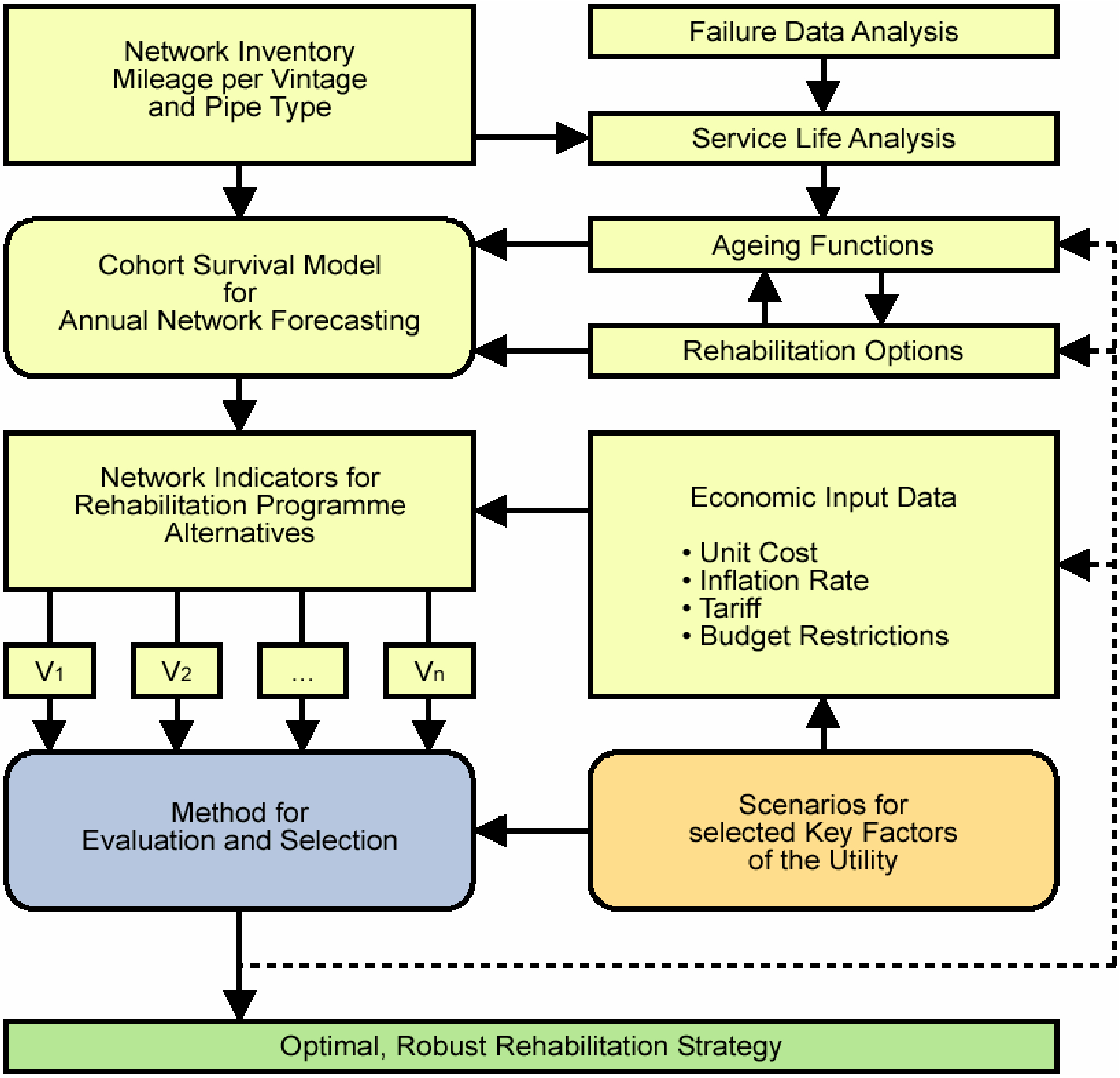

Figure 1: Extended *KANEW* Framework

This extended *KANEW* framework includes the "Scenario Writer" for utility background scenarios and the "Rehab Strategy Evaluator" for the evaluation of rehab strategies. The *KANEW* approach is recommended by the German Association of Gas and Water Works (DVGW) in guidelines G401 / W401 as a method for long term forecast of rehabilitation needs of gas and water supply networks. There is a series of applications of this approach to drinking water and gas networks [DVGW 1997, 1999].

This report describes the development of the **Rehab Strategy Manager** within WP4 in the context of the CARE-W project.

2 Methodology and Analysis

2.1 The KANEW Approach

Ageing processes can be described mathematically as age-dependent probabilities of changing into worse conditions, such as living or dead, sound or failed, function or malfunction. These rates of change, rates of death or rates of failure vary with the progression of age, depending on material and stress, and are functionally linked with probabilities of survival and life expectation, more generally expressed as the probability to be in a specific condition and hence to reach a corresponding age. Such relations have been used in cohort survival models in demographics and economics since the fifties to forecast the natural movement of population and to maintain accounts of capital stock [Herz 1994,1996a,b,1998].

In the KANEW approach, future annual rehabilitation needs are forecast in the long term by using the cohort survival model. Thus, future financial needs are calculated year by year and different rehabilitation strategies can be evaluated.

To a large extent, rehabilitation needs of infrastructure networks depend on the length of pipes, which were installed in past periods with different materials and techniques. The service life of specified pipe types are estimated in ranges from previous failure and renewal rates. Thus the length of pipe types reaching the end of their service life is calculated and summed up yielding the network rehabilitation rate which should be attained.

Based on these estimates of annual rehabilitation needs for different pipe types, medium term rehabilitation programmes can be defined and their investment costs calculated with corresponding unit costs for specified rehabilitation technologies. Medium and long term effects of rehabilitation programmes on failure rates, network age, residual service life, leakage and repair costs simulated and evaluated by dynamic investment calculus.

Utilities can choose from a wide range of options to find an appropriate long range network rehabilitation strategy, such as the extent of

- rehabilitation versus spot repair,
- replacement versus relining,
- no dig versus open ditch replacement,
- replacement alone versus together with other public works in the street,
- metallic versus other pipe materials,
- areawide versus sectionwise rehabilitation.

Any combination of these elements will have specific effects on the performance of the system in the short and long range.

The *KANEW* model requires input data on the mileage of pipes and on their ageing behavior. Starting point of the ageing process is the year or period of installation. So it must be given for each pipe that still is in service.

For various reasons it is important to establish pipe types. The utility will be interested to know, for example, the mileage of pipes by material and diameter that need rehabilitation in future years. Some categories of pipes may need relining, others replacement, some will typically show incrustation, others external corrosion.

Pipe types should also be defined with respect to differences in life expectancies in order to get better forecasting results. Fully protected ductile iron pipes will last longer than small diameter grey cast iron pipes, for example, and a relined old pipe will have a smaller residual life-span than a new one that has replaced the old one.

Pipes can be categorized according to major factors of influence on their ageing behavior such as material, diameter, technology of joints, stress and bedding quality, if such information is available together with the main’s length and period of installation. In general, it is recommended not to define pipe types with a fraction of less than 1 % of the total network mileage because such small categories will have only marginal effects on the forecasting results.

The more categories of pipes there are, the more difficult it is to make consistent estimates of their life-spans. For old pipes, there is some empirical evidence on their ageing behavior and replacement, however, there is very little empirical evidence on how long the newly installed pipes of new materials will last. Failure statistics often do not refer to the age of specific types of pipes, nor do rehabilitation statistics. Therefore, at least for some categories of pipes, intelligent guesses have to be made about the age that would be reached by certain percentages of them. Survival curves from utilities provide some orientation and might help to re-adjust first round estimates. However, the local situation should always been taken into account and lower and upper bounds should always been given.

Realistic estimates of the mains life-span are the most crucial model input. They must be based on local experience and statistics of failures and rehabilitation activities in the past and should reflect past and future rehabilitation policies.

The average service life of a particular pipe type might be in the range of 60 to 80 years. How will the life-spans be distributed around these two median points of age? Bell shaped or skewed distributions with the longer tail towards the older ages are more realistic than a uniform distribution over a smaller or larger period of time. It is recommended to estimate, in addition to the median service life, two points of age that would be reached by two specific percentages of each particular type of water mains. First, the age up to which no rehabilitation work would be done, just spot-repair in case of failure. This 100 % point of the survival curve represents the so-called resistance time, which is one of the parameters of the survival function. Resistance time is large, maybe 30 to 50 years, where fire brigade policy prevails, with lots of cheap spot-repair instead of expensive preventive rehabilitation. Spot-repairs do prolong the service life of water mains, increasing its life expectancies in general. The second point on the survival curve should be far beyond the median age and present some most resistant part of each particular type of pipes. It is recommended to specify the age interval within which the last 10 % of the particular type of pipe will still be in service. Of course, this interval will be larger than the intervals for the median age or the resistance time.

With these three points, a mathematical survival function is fitted to each pipe type and other ageing functions such as the rehabilitation rate, the service life density function and the residual service life expectancy is derived (Figure 2). Whereas, in principle, there are several probability density functions such as the Exponential, Normal or Weibull distribution, a special function, the so-called Herz distribution was developed and implemented in *KANEW*, which has some nice and practical features, particularly for infrastructure elements [Herz 1994,1996a,b; Trujillo 1995].

The KANEW approach was originally developed in a research project supported by the AWWA-RF (American Water Works Association Research Foundation) and was applied in more than 20 case studies for water and gas utilities so far.

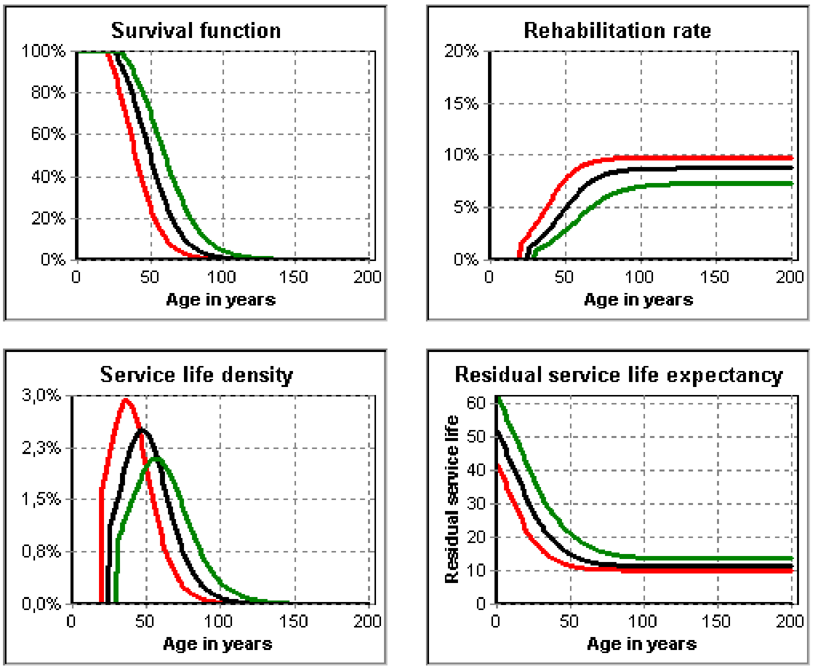

Figure 2: Ageing functions in *KANEW*

2.2 Long term strategic rehab planning within CARE-W

Long term strategic planning in the CARE-W project is used to estimate future rehabilitation needs and establish rehabilitation programmes in the medium term to develop the framework for annual rehabilitation planning and budget allocation, which is the theme of WP3.

The pre-existing *KANEW* approach is regarded as a good starting point for developing the **Rehab Strategy Manager**. The *KANEW* approach had to be advanced and enhanced within CARE-W, adding new components supporting long term strategic planning.

With this objective, several pieces of research have been carried out by CARE-W project partners. They have contributed to the development of the **Rehab Strategy Manager** with research on following subjects (table 1), which will be explained in subsequent chapters:

Table 1: Contributing work of the CARE-W partners

Task	**Partner**	**effort**
Define predictable Performance Indicators	LNEC	1 pm
Adapt individual pipe failure and reliability forecasting methods to the network level	NTNU	5 pm
Undertake empirical research on the pre-rehabilitation failure of water mains in relation to the network failure rate	SINTEF WRc BUT	1 pm 2 pm 2 pm

pm – person month

2.2.1 Predictable Performance Indicators

A system of Performance Indicators (PI) related to rehabilitation aspects in water utilities has been developed in WP1. Thus LNEC, responsible for WP1, should investigate, which PI's are suitable to long range forecasting within the **Rehab Strategy Manager** tool. The working specification for LNEC was stated as follows.

> "Whereas Performance Indicators are mainly used for monitoring and target setting, some of them may be predictable on a longer horizon (not just by extrapolation or expert estimation). Within the **Rehab Strategy Manager**, network performance indicators that are closely related to the intensity of network rehabilitation at any point in time (as specified, e.g. in a 5 year rehab programme), should be simulated as a function of the rehab measures taken.
>
> In *KANEW*, as it stands, this is done with respect to
>
> - the number of failures in the network (specified with respect to types of pipe)
> - the amount of water lost by leakage (specified with respect to types of pipe) as
>   a function of the number of failures (with specific leakage volume per failure)
> - the distribution of (types of) pipes by age (or any percentile)
> - the distribution of residual service lives of (types) of pipes (or any percentile).
>
> There may be other predictable PI worthwhile being simulated with some intelligent assumptions. The challenge for LNEC is to spend one person-month of creative thinking on which of their PIs are predictable within such a network rehab simulation model and what assumptions could be made to do this in a rather realistic way.
>
> So, LNEC should look at the basic variables that define predictable PIs, particularly those that were regarded as predictable according to the questionnaire "Choice of performance indicators for rehabilitation activities". We would like to include into the **Rehab Strategy Manager** as many PIs as possible! However, we want LNEC to stick to physical units, not extend their creative thinking to economic evaluation or to PIs measured in monetary units. This will be done in another, separate step (with appropriate costs and prices)."

The full report from LNEC was published already as "Report No 1.3 – March 2002" by LNEC [Baptista, Alegre 2002]. It is included in this report as appendix 1. We are summarizing the most important statements from this report here.

1. The 'control factors' of rehabilitation work should be expressed through following PI's:

Table 2: PI's related to rehabilitation work

Mains rehabilitation	%/ year	IWA code: Op15
mains relining	%/ year	IWA code: Op16
replaced or renewed mains	%/ year	IWA code: Op17
replaced or renewed valves	%/ year	IWA code: Op18
Service connection rehabilitation	%/ year	IWA code: Op19

Currently, only pipe**line** assets are forecast with *KANEW.* However the option to include other assets like valves, joints, hydrants etc. can be implemented without difficulties and will be available in the final version of *KANEW*. The type of future rehabilitation work can be defined by new asset types standing for different rehabilitation techniques in the pre-existing *KANEW* version. Thus, in the **Rehab Strategy Manager**, the set of control factors proposed by LNEC is already included.

2. From the whole set of Performance Indicators LNEC outlined to use following PI to describe the impacts of rehabilitation work:

Table 3: PI's related to impacts of rehabilitation programmes on network performance

	PHYSICAL INDICATORS		
1	Mains residual service life	years	Code: Ph15
2	Service connection residual service life	years	Code: Ph15a
	OPERATIONAL INDICATORS		
3	Mains failures	No./ 100 km/ year	IWA code: Op26
4	pipe failures	No./ 100 km/ year	Code: Op26a
5	joint failures	No./ 100 km/ year	Code: Op26b
6	valves failures	No./ 100 km/ year	Code: Op26c
7	service connection insertion point failures	No./ 100 km /year	Code: Op26d
8	Service connection failures	No./ 1000 connections/year	IWA code: Op27
9	Real losses	l/ connection/ day	IWA code: Op24
10	Infrastructure leakage index	-	IWA code: Op25
	QUALITY OF SERVICE INDICATORS (QoS)		
11	Pressure of supply adequacy	%	IWA code: QS9
12	Water interruptions	%	IWA code: QS11
13	Water taste	%	Code: QS16a
14	Water colour	%	Code: QS16b

The grey marked PI's are those that are already predicted by the **Rehab Strategy Manager**.

Joints (5), valves (6) and service connections (7) can be included without major difficulties into the Rehab Strategy Manager using the "pipe type definition" section. This section will be renamed accordingly to “Asset type definition”. Using different stock datasets one can forecast future rehabilitation needs for every single asset or for combinations of assets.

The “Infrastructure index”, standing for the percentage of water losses, can be calculated simply using the PI “Water produced” (m^3/year, Code A7) as reference from the PI tool during the calculation of future leakage in the **Rehab Strategy Manager**.

Since the **Rehab Strategy Manager** does not forecast on the single pipe level, there is no way to forecast the QoS indicators (11, 13, 14) until now, because they are closely related to problems in a specific geo-referenced area.

The QoS indicator “Water interruptions” (12) could be predicted as shown in the following example:

Failure rate: 2 F. / (km*a) , Average duration of interruption: 10 h/F.

Water interruptions [%] = 2 F. / (km*a) x 10 h/F. / 8760 h of service/(km*a) = 0,228 %

However, the number of people affected by a water interruption cannot be calculated without geo-referenced data. Thus this information cannot be included on the network level.

The above mentioned PI’s are included in the final version of the **Rehab Strategy Manager**.

2.2.2 Failure and Reliability Analysis and Forecast

The prediction of failures is an essential element within the forecast procedure. Based on the development of the number of failures, several indicators such as future repair costs, savings from reduced repair, balance between investments and saving etc. are calculated.

Currently, future failure rates on the pipe type level are easily calculated starting from the current failure rate of a pipe type and an annual increase [%] for that particular pipe type. In CARE-W this calculation method should be enhanced and NTNU should do a 5 person month research work on bridging the gap between failure forecasting models on the single pipe level and the network level used in WP4.

The working specification for NTNU (Jon Røstum in person) was:

> “Jon Røstum has volunteered to do and direct substantial research on how to bridge the gap between the individual pipe level and the network level, at which this long-term Rehab Scenario Manager must operate. In addition to the somewhat lengthy procedure of forecasting effects of all individual pipes, and summing up the results, a short-cut path should be detected based on the more sophisticated forecasting methodology of individual pipes for pipe aggregates, such as for pipe types with distinctive ageing behaviour. This research should be carried out in close co-operation with the Dresden team, if it is to be included into the Rehab Scenario Manager.”

NTNU has outlined 2 ways for the improvement of the existing failure forecasting methodology:

1. **Failure forecasting results from WP2.** The failure forecasting tools produce prediction of failures for each pipe/group of pipes in the network.
2. **Simple curve fitting based on observed data (“light” WP2).** Based on historical failure data it is possible to generate simple plots of the observed number of failures for each group. This curve can be extrapolated by using simple curve fitting techniques. This option might be good enough for the purpose in WP4. If the user of the final software (i.e. prototype) will not apply all the different tools, but only carry out a long term forecast of rehab needs, this simple method is a good alternative.

The first option needs an active link between the **Rehab Strategy Manager** and the failure forecasting tools in WP2. Taking the effects of rehabilitation programmes into account, the failure forecasting in WP2 must be re-calculated year by year during the stepwise forecasting procedure, based on the updated stock data from the **Rehab Strategy Manager**.

The second option – the "light" WP2 – proposes the use of an approximated failure forecasting function derived from historical failure data for every pipe type. This function is a simple power function with the form

$$F(t) = a * t^{b}$$

where **a** and **b** are parameters derived from the failure curve approximation, and **t** is the number of forecasting years from some starting year.

The first option will be the appropriate one, but could only be provided in the final version of the **Rehab Strategy Manager**, if an **active** link between WP4 and WP2 can be created. This needs further investigations regarding interfaces between WP4 and WP2, preferably using the CARE-W database.

For this reason the second option will be included in addition to the existing failure forecasting procedure, which is based on an annual growth rate of failures (by type of pipe) estimated from an analysis of previous failure rates.

Another part of research was the exploration of network reliability measures and the way of including them in the Rehab Strategy Manager. The additional performance indicator **Network hydraulic reliability (Ph13)** [percentage of time with shortage of water] was suggested to be included in the forecast of W4. The calculation rule is stated subsequently.

"The *network hydraulic reliability* is calculated based on the availability for all nodes in the network."

However, in WP4 there is no geo-reference on the network level (the network being represented "as a point" with specific attributes). Thus Ph13 could only be calculated within WP2. An active link between WP4 and WP2 cannot be provided, because a hydraulic net model needs geo-referenced information of pipes. Rehabilitation work on the network level, used in WP4 during the forecast, does not provide such geo-referenced pipe-specific data. Therefore, it is suggested to use the PI "Water interruption", introduced in section 2.2.1 as an indicator for the network reliability.

The original report of NTNU is included in appendix 2.

2.2.3 Pipe Type Definition

In addition to the work described in section 2.2.2, NTNU has done some investigations on the definition of pipe types and the estimation of specific ageing functions.

From experiences with the pre-existing *KANEW* software, NTNU recommended to include additional support for grouping pipes into pipe types and assessing reliable values for the parameters of the ageing functions. The intention now is to provide this facility in an additional tool, where statistical analysis of the network can be done and the parameters for the ageing functions can be estimated by analysing the failure and renewal rates in the past.

This tool will be developed outside CARE-W and should be available as an add-on tool at the end of the project.

2.2.4 Rehab Efficiency

In the *KANEW* approach, the efficiency of a specific rehabilitation programme is simulated by a factor relating the failure rate of a pipe prior to rehabilitation, to the average network failure rate. So far, there exists only little empirical evidence for such a factor.

To provide more empirical evidence on this efficiency factor, WRc, SINTEF and BUT had to do some research on this subject. The specification of work is given subsequently.

> "The reduction of failures, bursts and water losses is the most indicator of the success of specific rehab programmes. This can be measured on the pipe level (assuming that new pipes show no failures - except for "infant mortality" - and will continue for many years (probably within our normal forecasting horizon) to have no failures (if the work has been carried out properly).
>
> Water utilities have different standards on the number of failures and bursts per pipe section or km of pipe, and period) that are tolerated before the pipe has to be renovated or replaced. This threshold depends, among other factors, on the level of failures, bursts and leakage in the total network. As the failure, burst and leakage rate is known at the outset (and in the past) as a network performance indicator, it would be useful to relate the performance of individual pipes at the time they were replaced or rehabilitated to the corresponding network performance at that time.
>
> In KANEW, a factor relating the behaviour of the individual pipe to the average network behaviour at any point in time is employed to simulate the efficiency of rehabilitation work. An empirical study from Germany revealed that the failure rate of rehabilitated pipes was two to three times higher than the average network failure rate (Müller, R. 1998, Diploma thesis at TUD on Rehab Strategies for the Drinking Water Network of the City of Chemnitz). The managers of this water utility had good reasons to assume that this factor will change over time, again depending on the network performance.
>
> Therefore, we need further empirical evidence on this relationship, and SINTEF, Brno and WRc have agreed to do this. In this empirical research, it is essential to use the same definitions on failures, bursts and leakage and to employ the measurement rules of the performance indicators of CARE-W WP1 established by LNEC."

SINTEF has analysed the rehabilitation work in the past in the Norwegian cities of Oslo and Trondheim. WRc's study is based on the rehabilitation work of Bristol, the CARE-W end user in UK, whereas BUT has done a failure data analysis of the Brno water network. Unfortunately, BUT could not provide any information on rehab efficiency so far, but they promised to go on with their research work on this subject. The main results of the studies are summarized in tables 4 and 5.

Table 4: Rehab efficiency factors for <u>renovated</u> pipes

Partner	Range of efficiency factor	Average efficiency factor
SINTEF	4.1 – 11.1	6.3
WRc	0.3 – 2.2	1.2
BUT	-	-

Table 5: Rehab efficiency factors for replaced pipes

Partner	Range of efficiency factor	Average efficiency factor
SINTEF	4.2 – 24.1	9.5
WRc	0 – 10.5	3.3
BUT	-	-

From these outcomes some conclusions can be drawn.

1. The range of rehab efficiency is quite large. Thus, it is necessary to analyse the specific local situation of the utility when determining the rehab efficiency factor
2. As stated in the report from WRc, high failure rates are not the main reason for rehabilitation. Therefore the **Rehab Strategy Manager** should consider rehabilitation work on other reasons than high failure rates (e.g. water quality problems) as well, where the efficiency factor will not be taken into account.
3. The ratio between the efficiency factor of replaced and renovated pipes is about **1.5**.
4. As stated in the report from SINTEF, the average rehab efficiency tends to decrease year by year because of decreasing failure rates due to the improvement of the network condition. This implicates a decreasing rehab efficiency. By now, a decreasing trend-function of rehab efficiency will not be included in the **Rehab Strategy Manager**. Further investigations about the characteristics of that curve are needed.

The full reports are included in the appendix 3 (SINTEF), appendix 4 (WRc) and appendix 5 (BUT).

3 Software Development

3.1 Development system analysis

As stated in the working description of WP4 the Rehab Strategy Manager is based on the *KANEW* software. The pre-existing *KANEW* software was programmed in MS ACCESS 95. Due to compatibility problems between different MS ACCESS versions and different language versions (English, German etc.), a complete re-programming of *KANEW* was initiated to avoid compatibility problems and dependencies from other software in the future.

Before starting the software re-programming, the development system had to be chosen. As there are various systems with different programming languages available, it was necessary to set up a list of general features of the future software in order to evaluate the development systems. The following reasons finally led to the decision in favour to *Borland Delphi*:

- Applications designed with *Borland Delphi* are compiled into executable files. Therefore, code execution is far faster than in systems using code interpreters.
- Applications designed with *Borland Delphi* are stand-alone and do not need additional software for execution. This prevents trouble in software usage and maintenance if the additional software is updated. This ensures the usability of the software, regardless of software packages and software versions that are installed in parallel. Furthermore, the requirements for the user are kept on a modest level.
- The source code of *Borland Delphi* is, with minor changes, compatible to *Borland Kylix,* which is a development system for Linux. This eases cross platform development and permits the development of Linux versions of the software if there is a need for it.
- *Borland Delphi* includes the mighty relational client-server database system *Interbase* which can be run as a desktop system as well. *Interbase* is available as an open source and causes almost no costs in software acquisition.

3.2 Workflow model

The workflow model of the software has been developed according to the working steps in the **Rehab Strategy Manager**. The graphical user interface itself was designed according to guidelines for windows based software using menus and button–bars as main navigation instruments. The intention was to keep the interface as familiar as possible to quasi-standard software like MS-Office. Additional elements like the button bar on the left side were added to ease the first steps of the software usage. The frames within the workflow model stand for the main working forms in the programme.

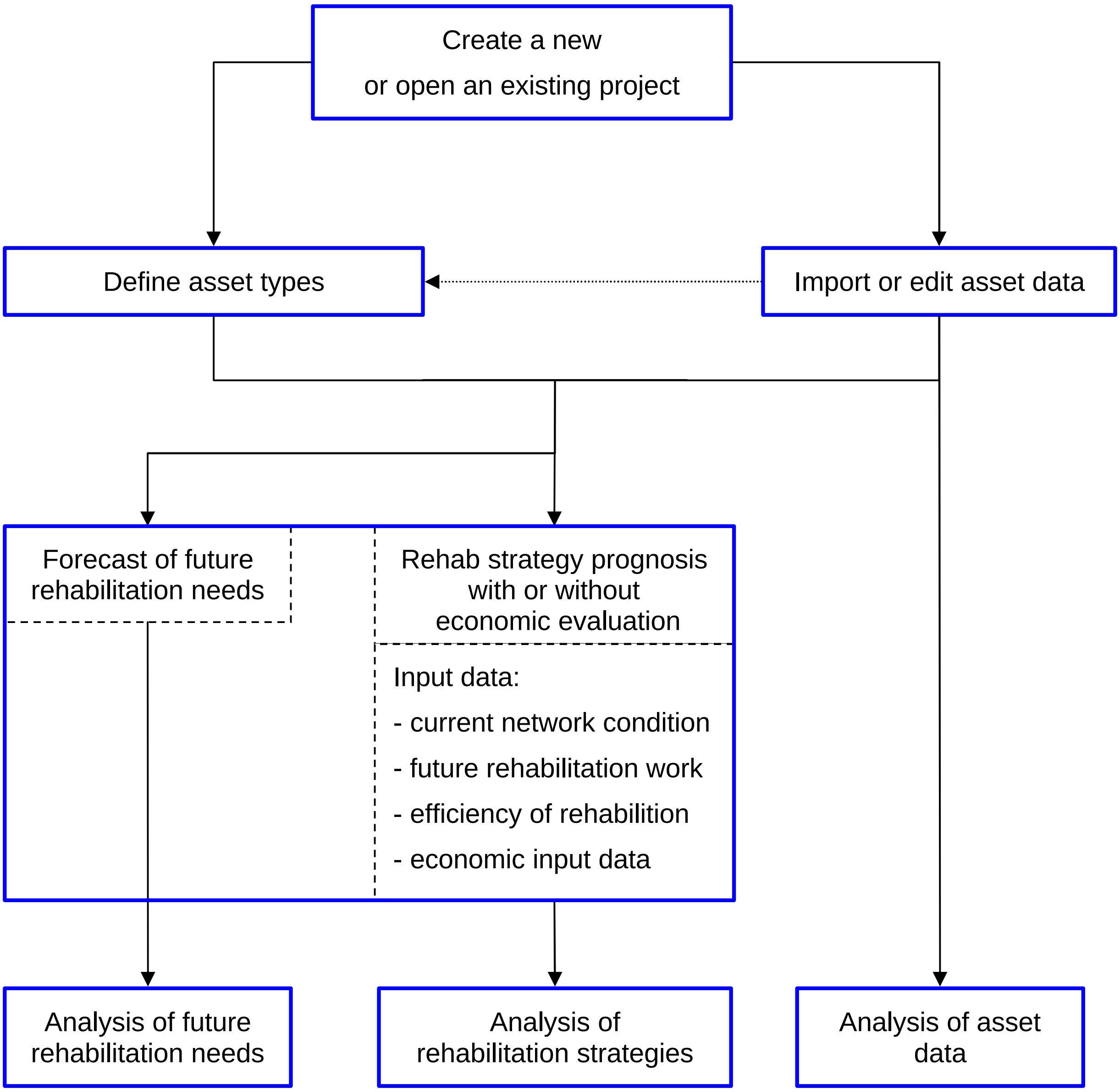

Figure 3: Workflow Structure Chart

3.3 Improvement of the Rehab Strategy Manager software

The evaluation of the first draw of the **Rehab Strategy Manager** – the beta testing phase – brought up questions and hints concerning misunderstandings, improvements of Graphical User Interface GUI, errors and bugs of the Scenario Writer. The main issues were the GUI and the connection of the software to the CARE-W prototype. All other comments referred to various minor items and were mainly caused by misunderstandings of the method behind the software. The testing phase will be continued during the case study to improve the usability of the software.

The CARE-W prototype has to connect the various tools of CARE-W and to handle the numerous data outputs and data requests of these tools. Therefore, most of the tools are designed as stand-alone applications with no direct data connection. The advantage of this procedure is the independence of all software developers of CARE-W once the interfaces between the different software tools are defined.

The data exchange via plain text files (semicolon separated csv-file) was selected as technique of the choice. Each developing team had to define their data requests and data outputs in a structured plain text import/ export file. All further development towards the connections between tools relies on these set definitions. The **Rehab Strategy Manager** software exports the forecasting results and can import asset data files. As the structure of the export file is defined, the CARE-W prototype can assemble new data exchange files for other tools if the required data provided from the **Rehab Strategy Manager**.

The included demo-project introduces a new user to the subject of long term strategic planning supported by a tutorial.

As CARE-W is a multi-national research project, it was decided to develop multilingual software with capabilities of language customisation by the user themselves. This eases the usage of the software, especially for future end users who didn't participate in the project and are not familiar with the research work behind the software.

A separate language translation tool is available for creating and modifying the user interface languages.

4 Summary

The **Rehab Strategy Manager** is the essential part of the extended *KANEW* framework for establishing appropriate rehab programmes. With relatively few data requirements the engineer gets a tool which accomplishes reliable long term rehabilitation planning. Together with the Rehab Scenario Writer and the Rehab Programme Evaluator an overall framework for long term strategic planning has been developed.

A description of the Strategy Rehab Manager software is available as a handbook – together with the software. All working steps are explained in detail to ease the applications first usage. The handbook is included in the software package and will be available in the Acrobat-PDF-format.

TU Dresden, responsible for WP4, would like to thank all CARE-W partners who have contributed to this task 2 of WP4, the development of the **Rehab Strategy Manager**.

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6 Appendices

6.1 Contribution of LNEC

CARE – W

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

Predictable performance indicators for long term rehabilitation planning

(Contribution of LNEC for WP4)

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Lisbon, February 2002

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Appendix

1 INTRODUCTION

This document is part of LNEC's contribution to WP4 and aims to respond to the specifications defined by the working group responsible, Dresden University, summarized as follows:

> *Specification of work for **LNEC***
>
> *Whereas Performance Indicators are mainly used for monitoring and target setting, some of them may be predictable on a longer horizon (not just by extrapolation or expert estimation). Within the Rehab Scenario Manager, network performance indicators that are closely related to the rate of network rehabilitation at any point in time (as specified, e.g. in a 5 year rehab programme), should be simulated as a function of the rehab measures taken.*
>
> *In KANEW, as it stands, this is done with respect to:*
>
> - *the number of failures in the network (specified with respect to types of pipe);*
> - *the amount of water lost by leakage (specified with respect to types of pipe) as a function of the number of failures (with specific leakage volume per failure);*
> - *the distribution of (types of) pipes by age (or any percentile);*
> - *the distribution of residual service lives of (types) of pipes (or any percentile).*
>
> *There may be other predictable PI worthwhile being simulated with some intelligent assumptions. The challenge for LNEC is to spend one person-month of creative thinking on which of their PIs are predictable within such a network rehab simulation model and what assumptions could be made to do this in a rather realistic way. So, LNEC should look at the basic variables that define predictable PIs, particularly those that were regarded as predictable according to the questionnaire "Choice of performance indicators for rehabilitation activities". We would like to include into the Rehab Scenario Manager as many PIs as possible! However, we want LNEC to stick to physical units, not extend their creative thinking to economic evaluation or to PIs measured in monetary units. This will be done in another, separate step (with appropriate costs and prices).*

2 METHODOLOGICAL APPROACH

2.1 Underlying assumptions

According to LNEC´s view, a key objective of long term rehabilitation planning is to predict the performance of a given water supply network at a future reference time when a rehab scenario is implemented, as well as the difference of performance between this scenario and the 'do nothing scenario' (Figure 1).

The long-term rehabilitation planning should take into account the '*control factors*' that the decision makers can play with, and predict the '*impacts*' on the system derived from the implementation of such decisions in order to allow for an easy comparison of the results of different options.

The core 'control factors' for long-term planning are the type and rate of the rehabilitation measures. Type includes mains relining, renewed or replaced mains, renewed or replaced valves and service connection rehabilitation. Rate is typically expressed in terms of percentage of the total mains length per year.

'Impacts' can be quantified in the form of the performance assessment of the system, technically and economically measured from the viewpoints of the physical assets, of the system operations and of the quality of the service provided. Not only the final performance derived from a given decision should be predicted, but also the performance variation between this situation and the 'do nothing' scenario is relevant.

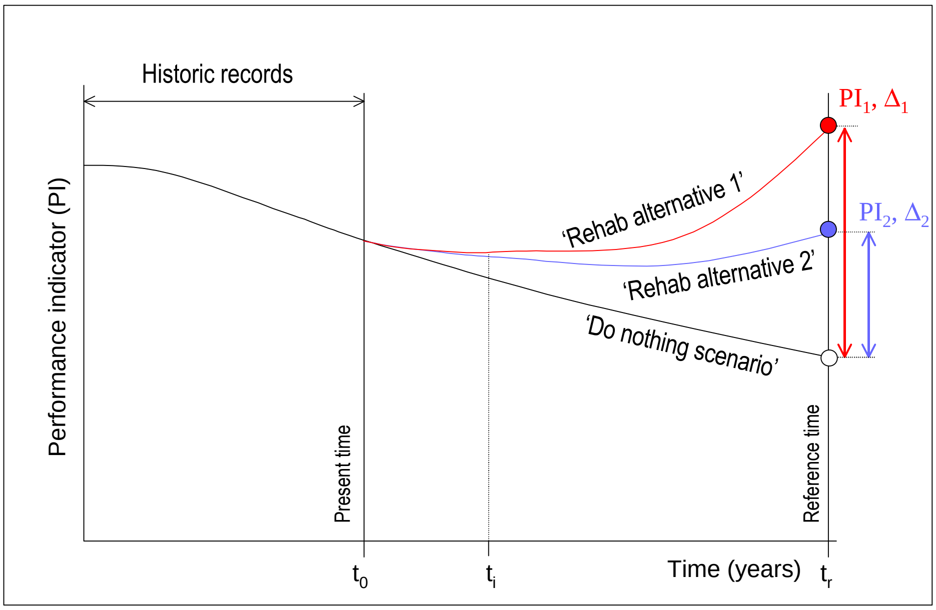

Figure 1 - Variables to be predicted for long-term rehab planning

Prediction of 'impacts' can be based on 'explanatory factors' that in some cases are controllable by the undertaking (e.g. service pressure, preventive maintenance practices) and in other cases are not, but will affect the system performance (e.g. soil characteristics, temperature).

2.2 Methodology for rehab long-term planning

As previously referred, the methodology for long-term planning requires the prediction of (i) the performance of a given water supply network at the reference time and (ii) the difference of performance between this scenario and the 'do nothing scenario'. Therefore, these are the two types outputs that the prediction model should produce.

The first stage consists of the predicting the PI curve between the present time and the reference time for the 'do nothing scenario', adopting a time series analysis to the historic records and extrapolating the results for the future. However, attention must be paid to the consistency of the historic records, as changes may have occurred in some of the factors influencing the PIs, therefore causing lack of homogeneity of series. Therefore, there is the need to identify the subset of factors that may have influenced the change of performance in the past, in order to assure that the prediction of the 'do nothing scenario' is reliable.

The next stage is the assessment of the performance for the given rehab scenario. The methodological approach proposed is as follows:

- select the rehabilitation 'control factor';
- define the corresponding rate;
- for each performance indicator selected, and for each time (t_i), according to a pre-defined time step (Figure 1):
  - apply the same function of the 'do nothing scenario' previously assessed to the part of the network that is not yet rehabilitated at a given time (e.g. 80% of the network that has not yet been rehabilitated in year t_i);
  - assess the improved performance of pipes rehabilitated in this time (e.g. 2% of pipes rehabilitated in year t_i);

- define and apply a performance evolution function (due to aging) to the pipes rehabilitated in previous times (e.g. 18% of pipes rehabilitated between the year t_0 and the year t_i);
- assess the final curve by a weighed average of the previous components.

2.3 Structure of this document

Based on the methodology presented in the previous sections, LNEC's contribution to WP4 focuses on the following aspects:

- Identification of the rehab PI related to the 'control factors'.
- Identification of all the rehab PI that one hand can measure the relevant 'impacts' for long-term planning and on the other hand are predictable.
- Identification of the 'explanatory factors' for each indicator selected, split into factors controllable by the undertaking in the short or medium term and any other relevant factors.
- Identification of the main 'explanatory factors' that can cause lack of homogeneity of the historic series.
- Identification of the 'explanatory factors' dependent on the 'control factors'.
- Identification of the dependency of 'control factors' on PIs.
- Assessment of prediction functions.

Each of these steps will be detailed in the following chapters.

Please note that the approach adopted aims to fit long-term water network rehabilitation planning regardless of the inputs and outputs of Kanew as it currently stands for. This means that adaptations of the conclusions presented, on the one hand, and of the Kanew itself as it currently stands for, on the other hand, will be necessary to achieve a satisfactory CARE-W long-term planning module (L-T CARE-W module).

3 IDENTIFICATION OF THE REHAB PI RELATED TO THE 'CONTROL FACTORS'

From the analysis of the rehab PI listing resulting from WP1 (Report No. 2) and reproduced in Appendix 1, the indicators that better allow to express the alternative options for rehabilitation, and therefore are adequate to be the 'control factors' to be adopted by WP4 are:

Mains rehabilitation	%/ year	IWA code: Op15
mains relining	%/ year	IWA code: Op16
replaced or renewed mains	%/ year	IWA code: Op17
replaced or renewed valves	%/ year	IWA code: Op18
Service connection rehabilitation	%/ year	IWA code: Op19

4 IDENTIFICATION OF PREDICTABLE PI TO ASSESS 'IMPACTS' OF REHABILITATION

This stage consists of a similar analysis of the rehab PI listing resulting from WP1, aiming to identify the rehab PI that on the one hand measure the impact of changes of any of the 'control factors' on the performance and on the other hand are predictable. 'Impacts' may be:

- on the physical system, taking into account that rehabilitation increases its residual life;
- on the operation, as rehabilitated pipes have less failures and water losses;
- on the quality of service, as rehabilitation may reduce pressure problems, interruptions and water quality degradation, improving that quality of service.

According to the terms of reference established by the WP4 co-ordinator, the economic and financial PIs have not been considered at this stage.

Results achieved are:

PHYSICAL INDICATORS		
Mains residual service life	years	Code: Ph15
Service connection residual service life	years	Code: Ph15a
OPERATIONAL INDICATORS		
Mains failures	No./ 100 km/ year	IWA code: Op26
pipe failures	No./ 100 km/ year	Code: Op26a
joint failures	No./ 100 km/ year	Code: Op26b
valves failures	No./ 100 km/ year	Code: Op26c
service connection insertion point failures	No./ 100 km /year	Code: Op26d
Service connection failures	No./ 1000 connections/year	IWA code: Op27
Real losses	l/ connection/ day	IWA code: Op24
Infrastructure leakage index	-	IWA code: Op25
QUALITY OF SERVICE INDICATORS		
Pressure of supply adequacy	%	IWA code: QS9
Water interruptions	%	IWA code: QS11
Water taste	%	Code: QS16a
Water colour	%	Code: QS16b

5 IDENTIFICATION OF THE 'EXPLANATORY FACTORS'

According to Appendix 1, the 'explanatory factors' for each indicator selected above have been identified, split into factors controllable by the undertaking in the short or medium term and any other relevant factors. The basis for work is the listing of utility information (UI) and external information (UI) that resulted from WP1 (Report No. 2).

Results achieved are:

	Controllable explanatory factors[1]	**Other explanatory factors**[1]
PHYSICAL INDICATORS		
Mains residual service life	service pressure, water quality, inspection, preventive maintenance and repair.	**mains materials, protection, age**, diameters, joint type, joint materials, location, bedding type, backfilling soil type, # service connections, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, traffic class, interference with other infrastructures, seismic conditions, **history of previous failures**[2]
Service connection residual service life	service pressure, water quality, inspection, preventive maintenance and repair, service connection failures.	**service connection materials, protection, age**, diameters, location, bedding type, backfilling soil type, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, traffic class, interference with other infrastructures, seismic conditions, **history of previous failures**[2]
OPERATIONAL INDICATORS		
Mains failures	service pressure, water quality, inspection, preventive maintenance and repair	**pipe materials**, **protection**, **age**, diameters, **joint type**, joint materials, location, bedding type, backfilling soil type, **# service connections**, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, **traffic class**, interference with other infrastructures, seismic conditions, **history of previous failures**[2]
pipe failures	service pressure, water quality, inspection, preventive maintenance and repair	**pipe materials, protection, age**, diameters, location, bedding type, backfilling soil type, **# service connections**, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, **traffic class**, interference with other infrastructures, seismic conditions, **history of previous failures**[2]
joint failures	service pressure, water quality, inspection, preventive maintenance and repair	**joint type, joint materials, age**, diameters, location, bedding type, backfilling soil type, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, **traffic class**, interference with other infrastructures, seismic conditions, **history of previous failures**[2]

---

[1] Explanatory factors considered to be more relevant are presented in bold.

[2] Experience shows that when a failure occurs, the repaired pipe tends to be more fragile and therefore the probability that a new failure occurs in the same location increases. This affects the overall indicator (mains failures), the pipe failures and the joint failures, but not so much the valve failures, the service connection insertion point failures or the service connection failures.

valves failures	service pressure, water quality, inspection, preventive maintenance and repair	**valve type, valve materials, age**, diameters, location, physical and chemical soil and groundwater characteristics
service connection insertion point failures	service pressure, water quality, inspection, preventive maintenance and repair	**type of insertion, age**
Service connection failures	service pressure, water quality, inspection and maintenance, preventive maintenance and repair	**service connection materials**, protection, **age**, diameters, location, bedding type, backfilling soil type, # service connections, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, traffic class, interference with other infrastructures, seismic conditions
Real losses	service pressure, water quality, inspection and maintenance, **preventive maintenance** and repair	**pipe materials**, **protection**, **age**, diameters, joint type, joint materials, location, bedding type, backfilling soil type, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, traffic class, interference with other infrastructures, seismic conditions, valve type, valve material, valve age
Infrastructure leakage index	service pressure, water quality, inspection and maintenance, **preventive maintenance** and repair	**pipe materials**, **protection**, **age**, diameters, joint type, joint materials, location, bedding type, backfilling soil type, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, traffic class, interference with other infrastructures, seismic conditions, valve type, valve material, valve age
QUALITY OF SERVICE INDICATORS		
Pressure of supply adequacy	service pressure (operational scenarios), inspection, preventive maintenance and repair	**demand, pipe materials, age, diameters,** network topology, topography, valve type, valve material, valve age
Water interruptions	service pressure, inspection, preventive maintenance and repair	**pipe materials**, **protection**, **age**, diameters, joint type, joint materials, location, bedding type, backfilling soil type, **# service connections**, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, **traffic class**, interference with other infrastructures, seismic conditions
Water taste	inspection and maintenance, preventive maintenance	**mains and service connections materials, age, protection, protection age**
Water colour	inspection and maintenance, preventive maintenance	**mains and service connections materials, age,protection, protection age**

6 IDENTIFICATION OF THE MAIN ‘EXPLANATORY FACTORS’ THAT CAN CAUSE LACK OF HOMOGENEITY OF THE HISTORIC SERIES

The use of historic records to support the assessment of the ‘do nothing scenario’ functions should be preceded by a thorough critical analysis of their consistency / homogeneity. This can be done not only by using the adequate statistical tests of homogeneity, but also analysing whether significant changes in any of the explanatory factors occurred. From the above listed explanatory factors, some are typically stable in time, which means do not affect consistency / homogeneity, but others can vary rapidly, affecting them and deserving more attention.

The following listing identifies the later group, in order to assist this consistence analysis.

Controllable explanatory factors:

- service pressure: changes in the operational scenarios regarding pressure management (e.g. establishment or change of pressure zones);
- water quality: changes in the potentially aggressive parameters of the water due to change of water sources, treatment procedures or operational procedures (related to the mixing of water from different sources);
- inspection and preventive maintenance: changes in the inspection and preventive maintenance routines (e.g. active leakage control);
- repairs: use of different repair procedures (e.g. replacement of the full pipe between joints).

Other explanatory factors

- traffic class: changes of intensity or typology of the traffic;
- interference with other infrastructures: occurrence of major underground works that may have affected the structural stability of pipes;
- history of previous failures: abnormal incidence of failures in specific areas (that may affect the future performance of the mains);
- demand: rapid changes in the system demand (e.g. due to new buildings of high consumption).

If lack of homogeneity is detected, either a shorter series shall be used or correction procedures should be implemented, if possible.

7 IDENTIFICATION OF THE ‘EXPLANATORY FACTORS’ DEPENDENT ON THE ‘CONTROL FACTORS’

Depending on the type of rehabilitation, some of the explanatory factors are affected. The identification of these factors is relevant, because this will allow for selecting the performance indicators potentially affected by the implementation of each type of rehabilitation. Conversely, they become candidate parameters for the prediction models.

Results achieved are:

	Explanatory factor potentially modified by rehabilitation
Mains rehabilitation	Mains and valve materials, protection, protection age, pipe age, diameters, location, bedding type, backfilling soil type
mains relining	Protection, protection age
replaced or renewed mains	Pipe materials, protection, protection age, pipe age, diameters, joint type, joint materials, location, bedding type, backfilling soil type, type of insertion, age
replaced or renewed valves	Valve type, valve materials, valve age
Service connection rehabilitation	Service connection materials, protection, age, diameters, location, bedding type, backfilling soil type, type of insertion, age

8 IDENTIFICATION OF THE DEPENDENCY OF ‘CONTROL FACTORS’ ON PI

In this section is presented a matrix where for each ‘control factor‘ and each predictable PI to assess ’impacts’ of rehabilitation is possible to identify the ‘explanatory factors’ to be included in the assessment of prediction functions (the more relevant are in bold).

Performance indicator	Mains rehabilitation			Service connection rehabilitation
	Mains relining	Replaced or renewed mains	Replaced or renewed valves	
PHYSICAL INDICATORS				
Mains residual service life	**protection**, protection age	**mains materials**, **protection**, **age**, diameters, joint type, joint materials, location, bedding type, backfilling soil type	-	-
Service connection residual service life	-	-	-	**service connection materials**, protection, **age**, diameters, location, bedding type, backfilling soil type
OPERATIONAL INDICATORS				
Mains failures	protection, protection age	**mains materials, pipe age**, **protection**, protection age, diameters, location, bedding type, backfilling soil type	valve type, valve materials, valve age	-
pipe failures	protection, protection age	**mains materials**, **protection**, **age**, diameters, location, bedding type, backfilling soil type	-	-
joint failures	-	**joint type**, **joint materials**, **age**, diameters, location, bedding type, backfilling soil type	-	-
valves failures	-	-	valve type, valve materials, valve age	-
service connection insertion point failures	-	**type of insertion**, **age**	-	**type of insertion**, **age**
Service connection failures	-	-	-	**service connection materials**, protection, **age**, diameters, location, bedding type, backfilling soil type

Performance indicator	**Mains rehabilitation**			**Service connection rehabilitation**
	Mains relining	**Replaced or renewed mains**	**Replaced or renewed valves**	
Real losses	**protection**, protection age	**pipe materials, protection**, **pipe age**, diameters, joint type, joint materials, location, bedding type, backfilling soil type	valve type, valve materials, valve age	**service connection materials, protection**, **pipe age**, diameters, joint type, joint materials, location, bedding type, backfilling soil**, age, type of insertion**
Infrastructure leakage index	**protection**, protection age	**pipe materials, protection**, **pipe age**, diameters, joint type, joint materials, location, bedding type, backfilling soil type	valve type, valve materials, valve age	**service connection materials, protection**, **pipe age**, diameters, joint type, joint materials, location, bedding type, backfilling soil**, age, type of insertion**
QUALITY OF SERVICE INDICATORS				
Pressure of supply adequacy	-	**pipe materials, pipe age, diameters**	valve type, valve materials, valve age	-
Water interruptions	-	**pipe materials, protection, pipe age**, diameter, joint type, joint materials, location, bedding soil type, backfilling soil type.	valve type, valve materials, valve age	-
Water taste	protection, protection age	**pipe materials**, , pipe age **protection**, protection age	-	**service connection materials**, **protection**, **age**
Water colour	protection, protection age	**pipe materials**, , pipe age **protection**, protection age	-	**service connection materials**, **protection**, **age**

9 ASSESSMENT OF PREDICTION FUNCTIONS

As explained in section 2.2, prediction of ‘impacts‘ from rehabilitation requires the assessment of the immediate improvement of performance derived from rehabilitation for each type of control factor, as well as the definition of the aging functions of the rehabilitated pipes.

These functions, to be developed in WP4 by Dresden University, have to be assessed from real data, and clustered by the respective key explanatory factors, identified in the previous Chapiter.

10 SUMMARY AND CONCLUSIONS

In summary, the LNEC´s proposal is that CARE-W long-term rehabilitation planning uses the following sequential steps:

Step 1: Identification of the 'control factors' based on the rehab PI proposed on the Chap. 3 and referred above (Figure 2), according the type of rehabilitation selected:

- Mains rehabilitation (%/ year): Length of transmission and distribution mains rehabilitated during the year / total mains length x 100
  - mains relining (%/ year)
  - replaced or renewed mains (%/ year)
  - replaced or renewed valves (%/ year)
- Service connection rehabilitation (%/ year): Number of service connections replaced or renewed during the year / total number of service connections x 100

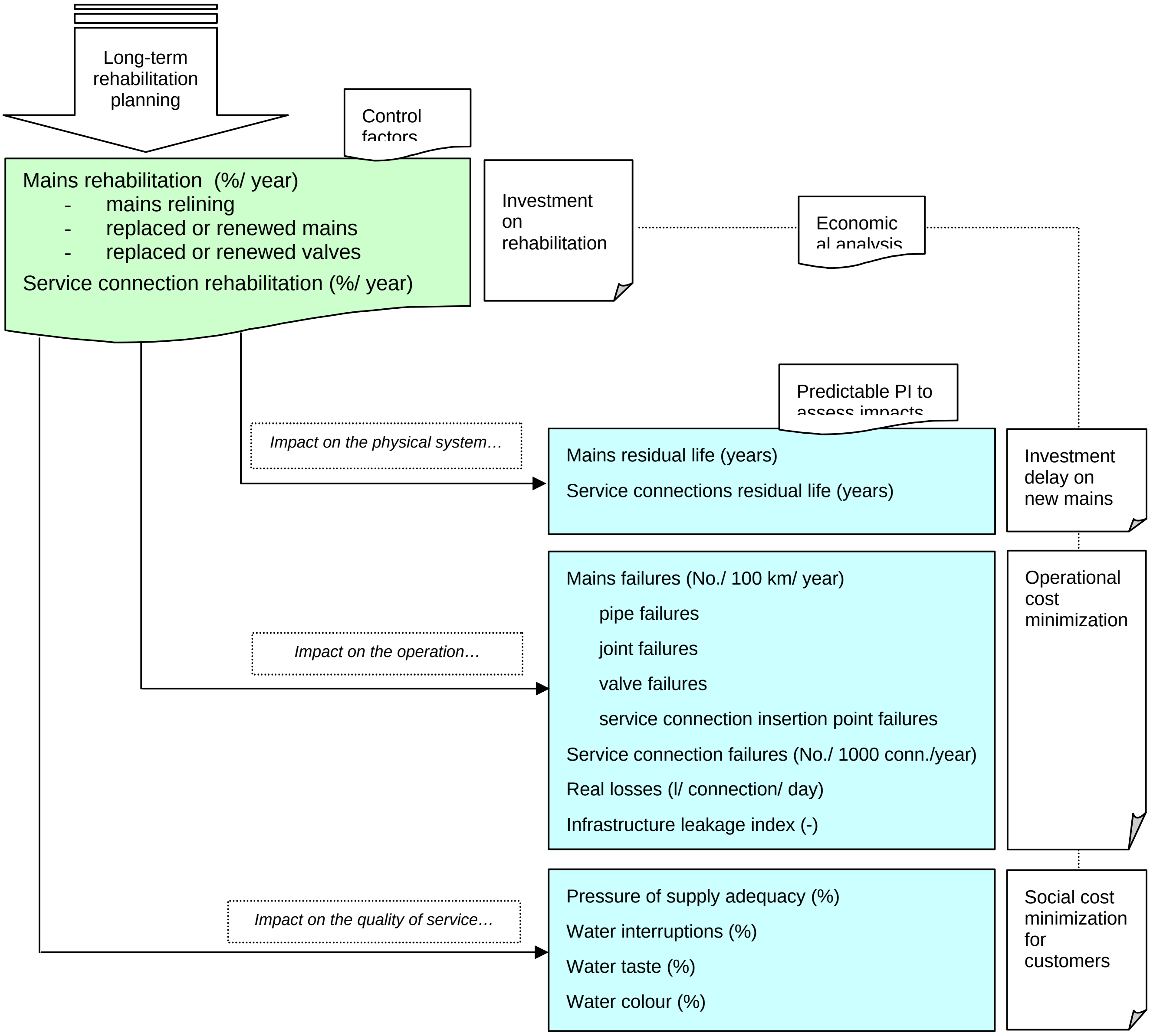

Figure 2 – CARE-W Rehab PI system to be included in WP4

Step 2: Identification of predictable PI to assess 'impacts' of rehabilitation (Figure 2), based on the rehab PI proposed on the Chap. 4 and referred above, but selected according the type of rehabilitation as presented on the Chap. 8:

Physical indicators:

- Mains residual life (years)
- Service connections residual life (years)

Operational indicators:

- Mains failures (No./ 100 km/ year): Number of mains failures during the year, including failures of pipes, valves, fittings and service connection insertion point failures / total mains length x 100
- Service connection failures (No./ 1000 connections/year): Number of service connection failures during the year / number of service connections x 1000
- Real losses (l/ connection/ day): Real losses x 1000 / (number of service connections x 365 x T/100) (T = % of year system is pressurised)
- Infrastructure leakage index (-): Real losses/ technical achievable low-level annual real losses (when system is pressurised)

Quality of service indicators:

- Pressure of supply adequacy (%): Number of delivery points that receive and are likely to receive pressure equal to or above the guaranteed or declared target level at the peak demand hour (but not when demand is abnormal) / number service connections x 100
- Water interruptions (%): Σ (Population subject to a water interruption x duration of the interruption in hours) / (population served x 24 x 365) x 100
- Water taste (%): Number of water taste tests of treated water complying with the applicable standards or legislation during the year / total number of water taste tests of treated water performed during the year x 100
- Water colour (%): Number of water colour tests of treated water complying with the applicable standards or legislation during the year / total number of water colour tests of treated water performed during the year x 100

Step 3: Prediction of the curve between the present time and the reference time for the 'do nothing scenario' (Figure 1), for each of previously selected PI, adopting a time series analysis to the historic records and extrapolating the results for the future, but only after a consistency analysis of the historic records based on the Chap. 6.

Step 4: Prediction of the curve between the present time and the reference time for the 'rehabilitation scenario' (Figure 1), for each of previously selected PI, adopting specific prediction functions that must include the relevant key 'explanatory factors' presented on the Chap. 8.

Step 5: Impact assessment for each of previously selected PI, and quantification of the performance variation between the 'rehabilitation scenario' and the 'do nothing scenario' at the reference time (Figure 1).

Step 6: Economical analysis (Figure 2) between the rehabilitation costs (resulting from Step 1) and the impact assessment (resulting from Step 5) regarding investment delay on new mains (physical indicators), operational cost minimization regarding reduction of water losses and repairs (operational indicators) and social cost minimization for customers regarding pressure, interruptions and water quality (quality of service indicators).

It is then possible to decide which scenario is the more convenient for the long-term rehabilitation planning.

Lisbon, February 2002

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Appendix

The following table reproduces all the rehab indicators of the control panel, according to the results of the WP1 2nd report (Report 1.2), identified as relevant for the CARE-W system. They include the PI required for the various modules of CARE-W prototype, as well as other PI relevant to support the diagnosis and decision-making phases of the rehabilitation process.

The PI's are grouped in five sections (the same adopted by IWA). For each indicator, the designation, the unit, the code, the predictability, the controlable prediction factors and other prediction factors are presented.

DESIGNATION	Unit	Code	Predictable for long term planning	Controlable prediction factors	Other prediction factors
WATER RESOURCES INDICATORS					
Inefficiency of use of water resources	%	WR1	no	-	
Resources availability ratio	%	WR2	no	-	
PHYSICAL INDICATORS					
Mains residual service life	years	Ph15	yes	service pressure, water quality, inspection, preventive maintenance and repair.	**mains materials, protection, age**, diameters, joint type, joint materials, location, bedding type, backfilling soil type, # service connections, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, traffic class, interference with other infrastructures, seismic conditions, **history of previous failures**[2]
Service connections residual service life	years	Ph16	yes	service pressure, water quality, inspection, preventive maintenance and repair, service connection failures.	**service connection materials, protection, age**, diameters, location, bedding type, backfilling soil type, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, traffic class, interference with other infrastructures, seismic conditions, **history of previous failures**[2]
Transmission and distribution storage capacity	days	Ph3	no	-	
Valve density	No./ km	Ph7	no	-	

DESIGNATION	Unit	Code	Predictable for long term planning	Controlable prediction factors	Other prediction factors
OPERATIONAL INDICATORS					
Failures and repairs					
Mains failures	No./ 100 km/ year	Op26	yes	service pressure, water quality, inspection, preventive maintenance and repair	**pipe materials**, **protection**, **age**, diameters, joint type, joint materials, location, bedding type, backfilling soil type, **# service connections**, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, **traffic class**, interference with other infrastructures, seismic conditions, **history of previous failures**[3]
pipe failures	No./ 100 km/ year	Op26a	yes	service pressure, water quality, inspection, preventive maintenance and repair	**pipe materials, protection, age**, diameters, location, bedding type, backfilling soil type, **# service connections**, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, **traffic class**, interference with other infrastructures, seismic conditions, **history of previous failures**[2]
joint failures	No./ 100 km/ year	Op26b	yes	service pressure, water quality, inspection, preventive maintenance and repair	**joint type, joint materials, age**, diameters, location, bedding type, backfilling soil type, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, **traffic class**, interference with other infrastructures, seismic conditions, **history of previous failures**[2]
valves failures	No./ 100 km/ year	Op26c	yes	service pressure, water quality, inspection, preventive maintenance and repair	**valve type, valve materials, age**, diameters, location, physical and chemical soil and groundwater characteristics
service connection insertion point failures	No./ 100 km /year	Op26d	yes	service pressure, water quality, inspection, preventive maintenance and repair	**type of insertion, age**
Critical mains failures	No./ 100 km/ year	Op26e	no		
Service connection failures	No./ 1000 connect-ions/year	Op27	yes	service pressure, water quality, inspection and maintenance, preventive maintenance and repair	**service connection materials**, protection, **age**, diameters, location, bedding type, backfilling soil type, # service connections, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, traffic class, interference with other infrastructures, seismic conditions

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[3] Experience shows that when a failure occurs, the repaired pipe tends to be more fragile and therefore the probability that a new failure occurs in the same location increases. This affects the overall indicator (mains failures), the pipe failures and the joint failures, but not so much the valve failures, the service connection insertion point failures or the service connection failures.

DESIGNATION	Unit	Code	Predictable for long term planning	Controlable prediction factors	Other prediction factors
Hydrant failures	No./ 1000 hydrants/ year	Op28	no	-	
Power failures	hours/ pumping station/ year	Op29	no	-	
Active leakage control repairs	No./ 100 km /year	Op5	no	-	
Water losses					
Water losses	m^3/ connection/ year	Op22	no	-	
real losses	l/ connection/ day	Op24	yes	service pressure, water quality, inspection and maintenance, **preventive maintenance** and repair	**pipe materials**, **protection**, **age**, diameters, joint type, joint materials, location, bedding type, backfilling soil type, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, traffic class, interference with other infrastructures, seismic conditions, valve type, valve material, valve age
Infrastructure leakage index	-	Op25	yes	service pressure, water quality, inspection and maintenance, **preventive maintenance** and repair	**pipe materials**, **protection**, **age**, diameters, joint type, joint materials, location, bedding type, backfilling soil type, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, traffic class, interference with other infrastructures, seismic conditions, valve type, valve material, valve age
Rehabilitation					
Mains rehabilitation	%/ year	Op15	no	service pressure, water quality, inspection and maintenance, preventive maintenance, mains failures, **rehabilitation** and repair	materials, protection, age, diameters, location, bedding type, backfilling soil type, # service connections, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, traffic class, interference with other infrastructures, seismic conditions
mains relining	%/ year	Op16	no	-	
replaced or renewed mains	%/ year	Op17	no	-	
replaced or renewed valves	%/ year	Op18	no	-	
Service connection rehabilitation	%/ year	Op19	no	service pressure, water quality, inspection and maintenance, preventive maintenance, mains failures, **rehabilitation** and repair	materials, protection, age, diameters, location, bedding type, backfilling soil type, # service connections, physical and chemical soil and groundwater characteristics, air temperature

DESIGNATION	Unit	Code	Predictable for long term planning	Controlable prediction factors	Other prediction factors
					(freezing probability), geotechnical conditions, traffic class, interference with other infrastructures, seismic conditions
QUALITY OF SERVICE INDICATORS					
Service					
Pressure of supply adequacy	%	QS9	possibly	service pressure (operational scenarios), inspection, preventive maintenance and repair	**demand, pipe materials, age, diameters,** network topology, topography, valve type, valve material, valve age
Water interruptions	%	QS11	possibly	service pressure, inspection, preventive maintenance and repair	**pipe materials**, **protection**, **age**, diameters, joint type, joint materials, location, bedding type, backfilling soil type, **# service connections**, physical and chemical soil and groundwater characteristics, air temperature (freezing probability), geotechnical conditions, **traffic class**, interference with other infrastructures, seismic conditions
Interruptions per connection	No./ 1000 connections	QS12	no	-	
critical interruptions per connection	No./ 1000 connections	QS12a	no	-	
Population experiencing restrictions to water service	%	QS13	no	-	
Days with restrictions to water service	%	QS14	NO	-	
Quality of supplied water	%	QS15	no		
aesthetic	%	QS16	no		
water taste	%	QS16a	yes	inspection and maintenance, preventive maintenance	**mains and service connections materials, age, protection, protection age**
water colour	%	QS16b	yes	inspection and maintenance, preventive maintenance	**mains and service connections materials, age,protection, protection age**
microbiological	%	QS17	no		
physical-chemical	%	QS18	no		
Customer complaints					

DESIGNATION	Unit	Code	Predictable for long term planning	Controlable prediction factors	Other prediction factors
Service complaints	No. complaints/ connection/ year	QS22	no	-	
pressure complaints	%	QS23	no	-	
continuity complaints	%	QS24	no	-	
water quality complaints	%	QS25	no	-	
water taste	%	QS25a	no	-	
water colour	%	QS25b	no	-	
interruptions	%	QS26	no	-	
critical interruptions	%	QS26a	no	-	
ECONOMIC AND FINANCIAL INDICATORS[4]					
Annual costs					
Unit total costs	€/m^3	Fi1	possibly		
unit running costs	€/m^3	Fi2	possibly		
Annual investment					
Unit investment	€/m^3	Fi18	possibly		
annual investments for new and upgrading assets	%	Fi19	possibly		
annual investments for assets replacement	%	Fi20	possibly		
Tariffs					
Average water charges for direct consumption	€/m^3	Fi21	yes		
Average water charges for	€/m^3	Fi22	yes		

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[4] As specified by Dresden University, this task did not include the analysis of economic and financial indicators.

DESIGNATION	Unit	Code	Predictable for long term planning	Controlable prediction factors	Other prediction factors
exported water					
Economical rehab assessment					
Balance of costs and benefits	€/year	Fi38	yes		
Internal rate of return	%	Fi39	yes		

6.2 Contribution of NTNU

CARE – W

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

Failure and reliability in long term planning- "The missing link between WP2 and WP4"

(Contribution of NTNU for WP4)

Jon Røstum
Researcher
Norwegian University of Science and Technology (NTNU)

Trondheim, June 2002

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1. Introduction

This document deals with WP4 – task 2 the development of the *Rehab Strategy Manager*. This document is part of NTNU's contribution to WP4 and aims to respond to the specifications defined by the working group responsible, Dresden University (TUD), summarized as follows:

> *From NTNU we are expecting 5 pm contribution on how individual pipeline failure and reliability forecasting methods could be integrated into the failure and reliability forecasting tool on the network or pipe category level.*

The existing *KANEW* software, which form the basis for the new *Rehab Strategy Manager* has been widely used in Norway in several case studies for both for water and wastewater networks. (Narvik, Trondheim and Sandefjord). This has been a valuable experience and these case studies have highlighted some needs for improvements in *KANEW*. These finding are also included in this report.

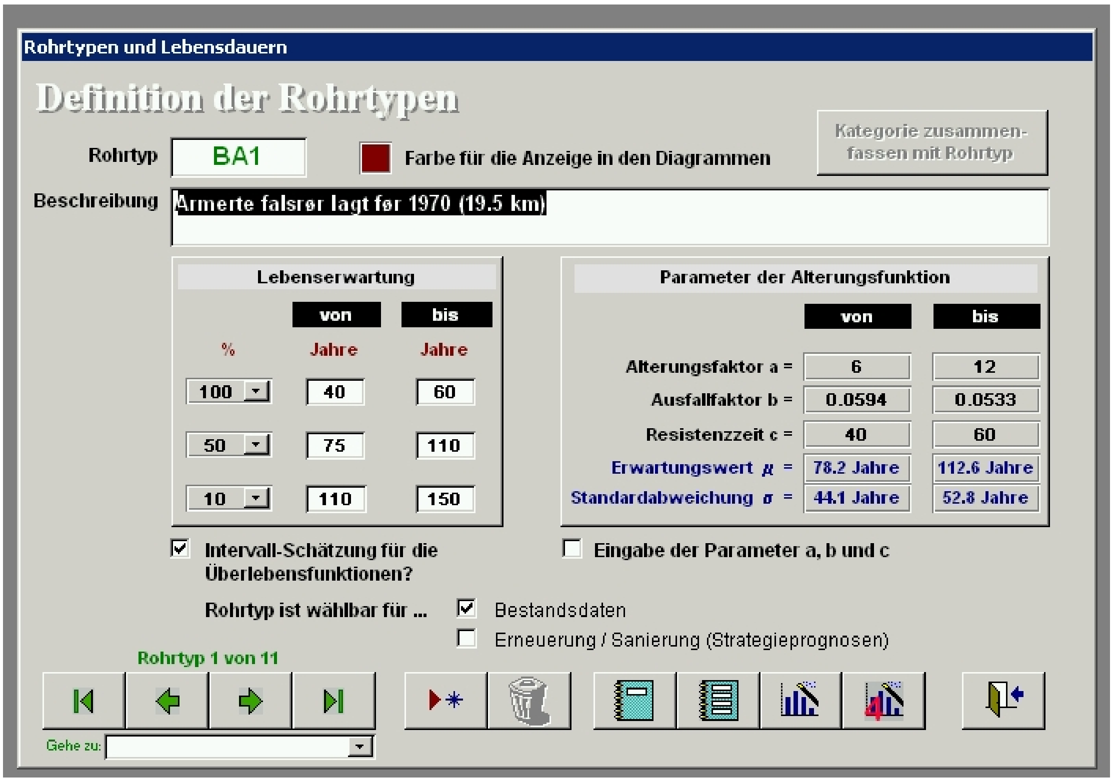
The following aspects related to development of the *Rehab Strategy Manager* in WP4 are discussed in this document:

1. Assessing survival functions (parameters) based on observed data
2. Improved pipe failure forecasting in WP4 at network level - link to WP2
3. Reliability measure at network level suggested as an additional performance measure to be included in the *Rehab Strategy Manager*
4. Grouping of pipes based on statistical analyses in WP2 (i.e. all the tools in CARE-W prototype should similar pipe groups in order to have a harmonised prototype)

2. Assessing survival functions based on observed data

The crucial point in the KANEW approach is the stipulation of the parameters in the ageing functions. Normally these functions are estimated based on assumptions on 3 values on the survival curve (i.e. the survival curve for not being replacement/renewed) - 100%, 50% and 10% age of survival. Based on these 3 point on each curve the parameters *a*, *b* and *c* in the survival function is calculated (see Figure 1).

Experience from applying the existing *KANEW* software for water networks in Norway indicates that there is a need for some type of *validation/assistance/ guidance* in how to assess the survival functions for each group of pipes. It might be an idea to include it as an add-inn tool, where the user of the software can decide whether or not he would like to validate the parameters or not.



Rohrtypen und Lebensdauern

Definition der Rohrtypen

Rohrtyp BA1 🟥 Farbe für die Anzeige in den Diagrammen

Beschreibung Armerte falsrør lagt før 1970 (19.5 km)

Lebenserwartung		
	von	bis
%	Jahre	Jahre
100	40	60
50	75	110
10	110	150

Parameter der Alterungsfunktion		
	von	bis
Alterungsfaktor a =	6	12
Ausfallfaktor b =	0.0594	0.0533
Resistenzzeit c =	40	60
Erwartungswert μ =	78.2 Jahre	112.6 Jahre
Standardabweichung σ =	44.1 Jahre	52.8 Jahre

☑ Intervall-Schätzung für die Überlebensfunktionen?

☐ Eingabe der Parameter a, b und c

Rohrtyp ist wählbar für ... ☑ Bestandsdaten
☐ Erneuerung / Sanierung (Strategieprognosen)

Rohrtyp 1 von 11

Figure 1 Definition of the pipe types in *KANEW* with the estimates of survival data and the corresponding parameters for the ageing functions.

Normally, KANEW is relatively robust in terms of small changes in the ageing parameters. However, if the average age of one of the groups is close to the expected liftetime of this specific pipe type, a small change have large influence. If the actual group is large (i.e. many km of pipes), this group will have large influence on the expenditures in the following years. Since the most interesting time horizon for long term planning is in the order of 10-20 years, other pipe types that are far from the end of their lifetimes, will have less influence on the overall results. Therefore, some type a validation of the parameters for the ageing function, at least for such “critical” pipe types, should have been offered. In the following a procedure for how this can be done is outlined.

2.1 Procedure

The ageing function in KANEW/Rehab Strategy Manager deals with replacement of pipes. In order to validate the parameters maintenance records are required (e.g. replacement data). This type of information is often recorded in the municipality. Based on these data it is possible to assess or at least limit the possible range of the parameter values.

Within the CARE-W framework a starting point might be the well-defined input files required for the failure forecasting models in WP2 (i.e. Assetmap1&2, Failnet- Stat and Winroc). These files include information about inventory data (e.g. material, length, installation year) and maintenance data (e.g. data of failure, replacement/renewal date, rehab type) for each pipe in the network. Based on these data it is possible to assessing the parameters in the survival functions in *KANEW*. As an alternative data source the GIS within CARE-W prototype can be used, but in WP2 the data format is already well defined. Some of this information is already being used in *KANEW*, but the use of the available data can be further improved.

If we want to estimate the parameters (*a*, *b*, and *c*) in the *Herz* distribution based on historical data, we can either start with the *density function*, the *survival function* or the *failure rate* (i.e. renewal rate). Since the *Herz* distribution is unique with respect to the tail-end of the renewal rate (the *b*-value is the asymptote), plotting the replacement curve provides useful information. The replacement function is given by:

$$h(t) = \frac{be^{b(t-c)}}{a + e^{b(t-c)}} \quad \text{for } t \geq c = 0$$

By just looking at the graph, two of the parameters in the distribution can be checked manually. No renewal before the age of *c* and an asymptotic value equal to *b*. From this starting point it is also easier to say something about how the curve should be modified in terms of non-complete replacement data which is always the case (i.e. the rehab history for all pipes in a group is not yet observed). The true survival function will only be known when all pipes have reached their end of their lifetime. However, it is not interesting to model the future behaviour of an already “dead” group. This illustrates the problem with assessing the parameters for the ageing functions. The process choosing parameters can be better handled by including some type of validation.

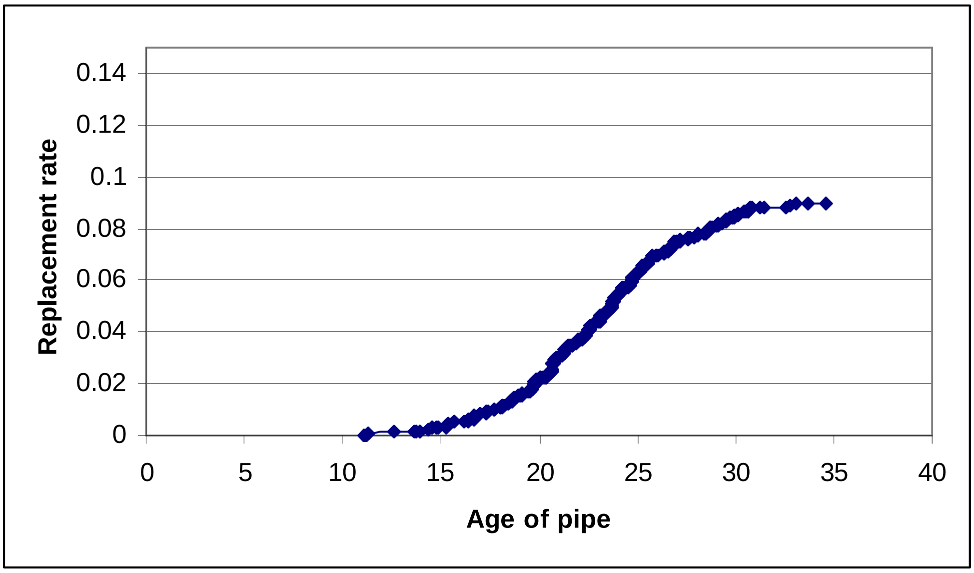


Figure 2 Replacement rate for DCI1 Trondheim

As an illustration of how the validation process can be carried out, data from Trondheim, Norway is used. The same data was also used for testing the forecasting models in WP2. Ductile iron pipes laid between [1963(-5)-1979] is analysed (the group is called DCI1). Figure 2 shows the replacement curve for this group. In Trondheim maintenance data is available from 1988. The first failures occurred early on these pipes (before 1988), but it is realistic to believe, than no or at least very few pipes have been replaced before 1988. This means that the starting point of replacement curve is known.

Since we in Figure 2 are dealing with the *age* of a pipe and not the *calendar* time, the replacement curve must be considered as a *lower bound estimate*. Some pipes, which still are younger than 35 years, might influence the slope of the curve in case they are replaced before they reach the age of 35 years (i.e. the curve will rise). Also the asymptotic level will be affected. This is illustrated in Figure 3.

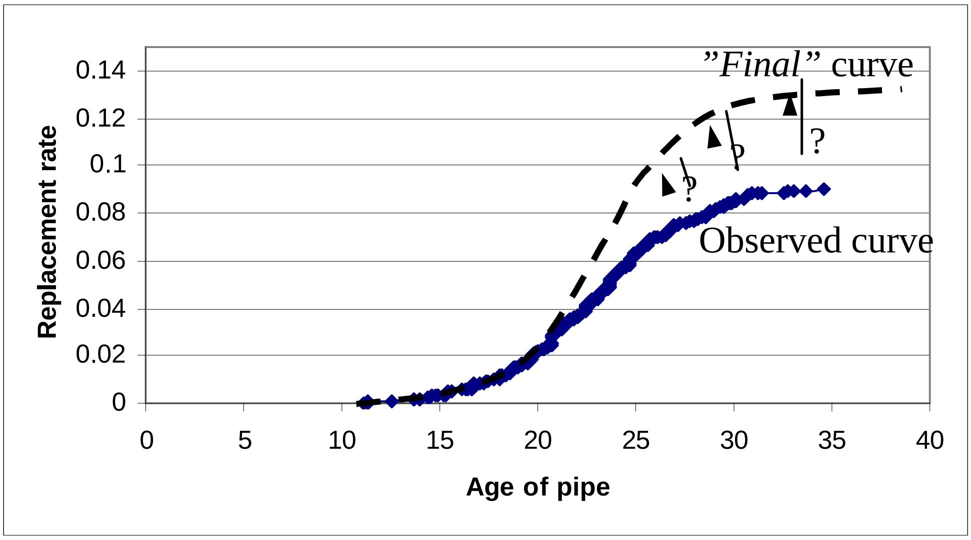


Figure 3 Illustration of future development of replacement curve for DCI1 in Trondheim.

Based on this curve we are able to say something about the starting point (*c*= 11), the slope of the curve (*a* –values greater than some value) and the asymptotic level (*b*> 0.09).

Instead of using the replacement curve as the starting point, an alternative way might be use the density function. The density function can be found by plotting the number of pipes being replaced for each age value. Standardization of such a curve gives us the density function (Figure 4). The density function and the replacement function are inter-related and give the same information. The density function has the same limitations as the failure rate/replacement curve with respect to non- complete replacement history.

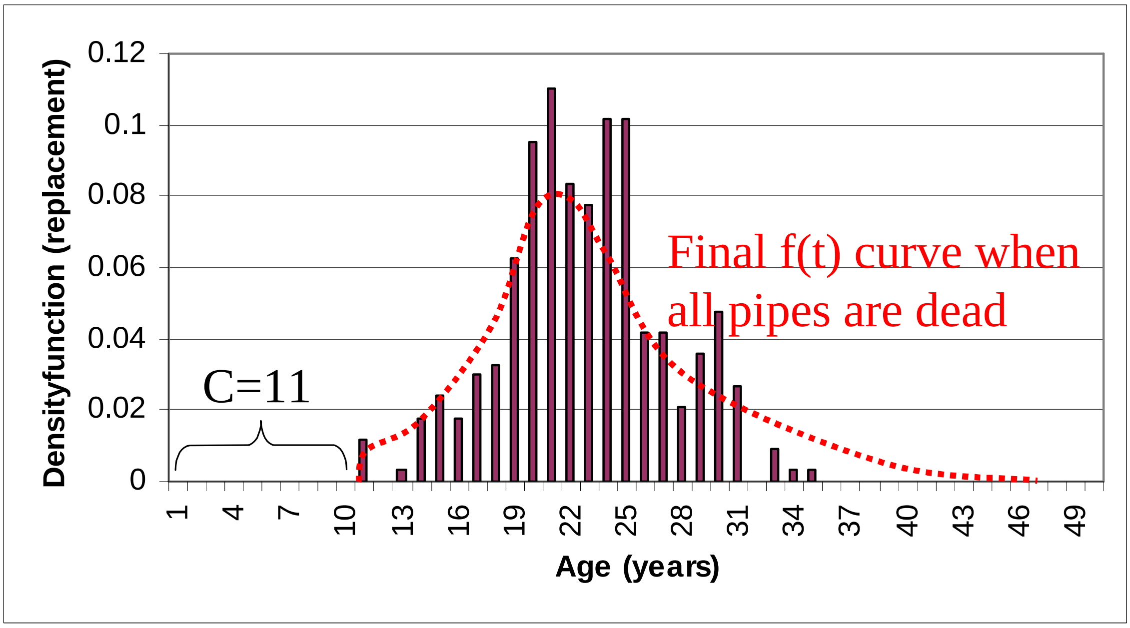


Figure 4 Density function for one pipe group in Trondheim (DCI1)

As the replacement history of this group continues, the curve will develop further. In Figure 4 the shape of the final curve is indicated. The curve will start at the same point (*c*=11), but the peak will be reduced and the tail end will be extended to the right (due to the fact that pipes which are still functioning will sooner or later also be replaced).

Regardless of the approach chosen for assessing/validating the parameters, this is a useful exercise. If we are able to give some guidance in how to assess the parameters/validation of the parameters, the link between the WP2 tools and the long-term planning will be stronger and thereby also the CARE-W prototype will be more successful. Nevertheless, the most important aspect is that the user of the software, will be more confident with the results and it will be easier to sell projects with the software.

3. Grouping of pipes based on statistical analysis in WP2

The statistical failure forecasting models in WP2, *WATERFOWL* and *KANEW* all introduce the concept of pipe categories for their own use. For these tools, the definition of categories is currently set at project level in the data map. In the failure forecasting models these categories are defined based on statistical analysis. Pipes with the same statistical behaviour are lumped together (significant difference between the groups in terms of break pattern). In *KANEW* also groups of pipes are lumped together in groups. The grouping of pipes in *KANEW* follows pipes with distinctive ageing behaviour. This means that each group has a unique ageing behaviour. The structural deterioration process is essential for generating the groups. This leads us to a link between the failure forecasting tools and the grouping of pipes in the *Rehab Strategy Manager*.

The CARE-W prototype will be more user-friendly if different tools (WP’s) use similar pipe groups. This is most important when the user will run a complete CARE-W procedure. Of course there might be situations where another grouping of the pipes is better. The problem with asbestos cement pipes illustrates this. The ageing behaviour of the pipes might be good enough, but the municipality may want to replace this group as soon as possible due to health risks. The *KANEW* approach is able to handle such situations. Nevertheless, in general it would have been user-friendlier if the groups had been more or less the same for all the tools.

4. Failure rate development in the Rehab Strategy Manager based on observed data- improved approach

The *Rehab Strategy Manager* (and the former *KANEW*) needs to know about the future failure development in order to estimate how much money is saved as a result of rehab activities in the network. The future expenditures are analysed for different levels of rehabilitation. The scenario " "*do nothing*", i.e. meaning that you continue to the do the same as before (same level of rehab included). This term is a bit confusing and instead the term "*status quo*" can be used indicating that you continue at the ongoing level of rehabilitation. For the status quo situation you use the same ageing functions resulting from historical maintenance data. This implies that you for the alternative scenarios do more or less than done before.

The existing approach is to assume a yearly increase in break rate (percentage increase per year). This approach is not good enough, since the total number is increasing every year and the percentage will not be constant even for a deteriorating network (the percentage will be reduced with time).

What's needed, is a forecast for each group of pipes estimating the total breaks per year. (i.e. a table with year and number of failures for each group). The necessary data (and results) are already available via WP2, since the failure forecasting models use historical break data to predict future pipe breaks.

The Rehab Strategy Manager has two possible routes for improving the existing failure rate development:

1. **Failure forecasting results from WP2.** The failure forecasting tools produce prediction of failures for each pipe/group of pipes in the network.
2. **Simple curve fitting based on observed data ("light" WP2).** Based on historical failure data it is possible to generate simple plots of the observed number of failures for each group. This curve can be extrapolated by using simple curve fitting techniques. This option might be good enough for the purpose in WP4. If the user of the final software (i.e. prototype) will not apply all the different tools, but only carry out a long term forecast of rehab needs, this simple method is a good alternative.

The table containing the information about the future failure development must be recalculated for each year in order to include the effect of rehab activities. In WP2 a special test (benefit index test) is calculated for evaluating the power of the failure forecasting models at pipe level. The benefit index test shows the number of avoided failures as a function of rehabilitated individual pipes. The test shows that the models are capable at pipe pointing out the worst pipes in the network. The results from the Benefit index test also indicates that a simple model (ranking of pipes according to number of failures and age) might be good enough for assessing the worst pipes in a group (<10% of pipes).

Table 1 shows an example of the data, which can be made available for the *Rehab Strategy Manager*. The simulation is carried out using the failure forecasting model *WINROC*.

Table 1 Forecasted failure per year for one group (DCI1)- for the *status quo* scenario

Year	Number of failures per year
2000	160
2005	170
2010	178
2015	184
2020	190

At network level all the failure forecasting models in WP2 are good enough for prediction.

The same information is also available via a cumulative plot/trend plot (Figure 5).

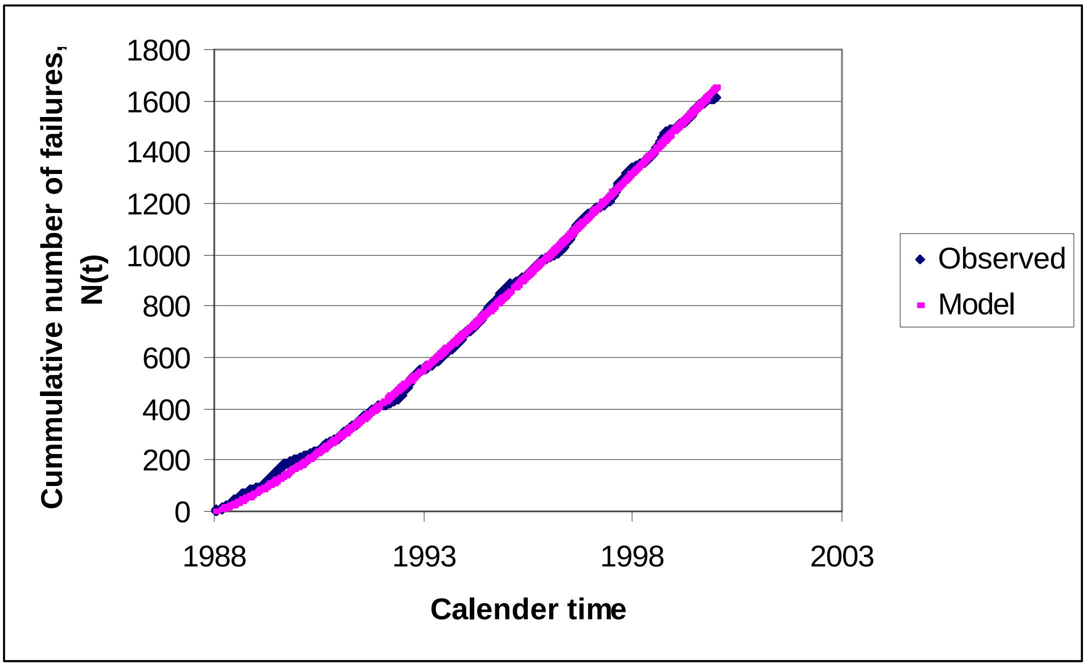


Figure 5. Cumulative numbers of failures for one pipe type (ductile iron pipes laid before 1980) in Trondheim (observed and modeled).

For some of the models in WP2 the trend is given for each individual pipe in the network easily (Winroc, Assetmap 1). The model with the best results at pipe level, Failnet- Stat, uses Monte Carlo simulation in one of the simulation steps. Generating trend curves for each group of pipes is more time- consuming for this model than the other failure forecasting models. However, if only a limited number year values are required and not a continuously time-series, it can easily be done.

As an alternative to using the results from the WP2 tools the observed failure data (or the input file) can be used directly. By plotting the cumulative number of observed breaks and just adding a simple trend curve, forecast for each group can be carried out. How this can be done is illustrated in Figure 6. The beginning of the curve is the same the curve in Figure 5, but the curve is also used for forecasting. A simple power function fits the data very well. By using the equation the number of failures in a given year can easily be calculated. Similar plots can be calculated for different level of rehabilitation (i.e. rehab scenarios).

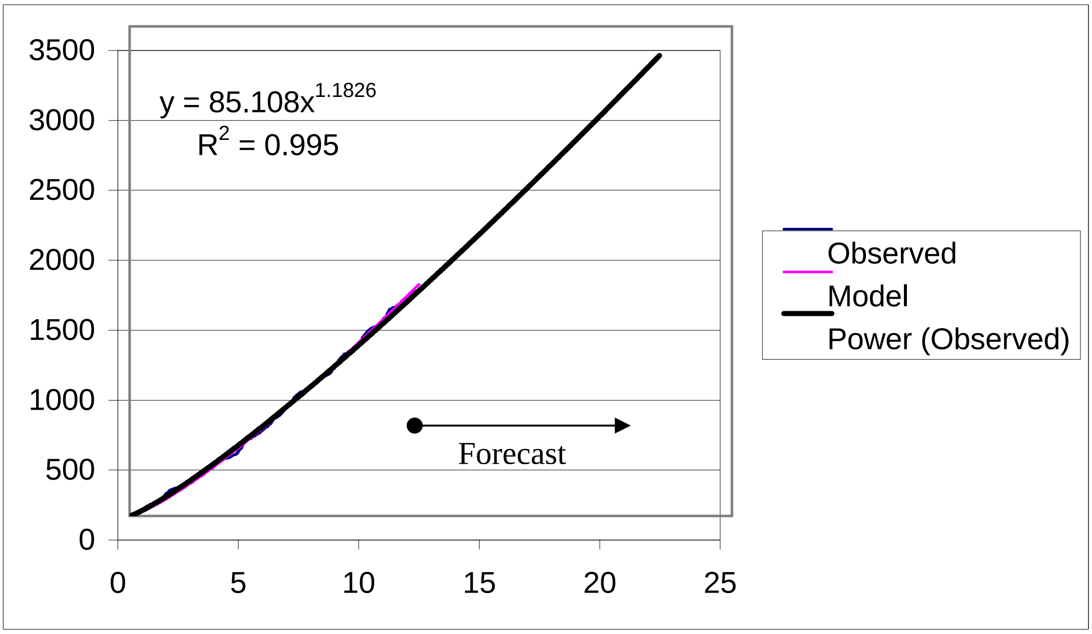


Figure 6 Forecast of breaks for group DCI1 in Trondheim (status quo alternative).

Linking the *Rehab Strategy Manager* to the results at pipe level in WP2 can also be done during the economic analysis. Instead of replacing the oldest pipes according to the survival function, the *worst* pipes with respect to breaks can be replaced for each time-step (year). Of course such an approach only makes sense when the time horizon is relatively short 10-20 years and the results for the failure prediction models are reliable. For a 100 years planning horizon this approach does not make sense, but such a long-time planning is seldom realistic anyway.

5. Reliability measure at network level as a new PI to be included in the Rehab Strategy Manager

TUD wishes to include, as many predictable PI is the Rehab Strategy Manager as possible. A predictable PI not mentioned in the list for the Rehab Strategy Manager (TUD document, specification of task 2, 14.11.01) is a *reliability* measure. It does make sense to include a reliability measure in the Rehab Strategy Manager. Such a measure will be predictable and also provides a new link to WP2, which is important for the CARE-W Prototype in order to avoid a lot of “*stand-alone*” tools.

Linking the reliability and the long-term performance of the system can be achieved in a similar way as the break rate development. However, it does not make sense to apply it at category level since the category is spread all over the network.

At *network/sector* level a useful performance indicator might be the:

> **Network hydraulic reliability (Ph13)** (Unit: [*percentage of time with shortage of water*], i.e. probability)

The *network hydraulic reliability* is calculated based on the availability for all nodes in the network. In the final report of WP1- report No 2 (Babtista and Alegre, 2002) Ph13 is included as an Additional Performance Measure (APM).

The reliability as a factor in long-term planning can also be dealt with in the Rehab Scenario Writer in the case of population growth and network extension for evaluating the effect on reliability. In the Rehab Scenario Writer (report D9), the soft forecasting tool, it is possible to include user-defined factors. Reliability might be one of these. In the last case there will be different scenarios for the future development of the PI.

In the following the network reliability measure is calculated by using the reliability model Aquarel in WP2. The expected value for each year is calculated based on the increase in break rate and increased pipe roughness. The future values for these parameters must be estimated. In Norway it can be assumed that the water consumption will be relatively constant within the next 10-20 years. For the pipe roughness there has been some research on how this increase with time. For ductile pipes the increase is in the order of 0,15-0,35 mm/year. Hydraulic simulation models often indicate roughness values at 5-10 mm for 30-50 year pipes. In average this gives us 0.1 mm/year as increase. (5 mm /50 year =0,1 mm/year). In the *AQUAREL* analysis an average value of 0.1mm/year is used.

Table 2 shows future development of the reliability measure for a small zone in Trondheim (Ugla). Similar analysis can also be carried out for the whole network. This type of data can be made available for the *Rehab Strategy Manager*.

Table 2 Forecasted overall reliability for the Ugla zone in Trondheim (Aquarel results)

Year	**Overall network reliability (probability)**	**Number of days with shortage of water**
2002	0.972	10.0
2012	0.970	11.1
2022	0.967	11.9

In average the downtime (percentage of time) for this zone will increase with 20%, equivalent to 2 days increase in water shortage per year within the next 20 years. Of course the number cannot be taken for granted, but it indicates a decrease in the reliability for the zone in the long term if you do nothing. For different alternative rehabilitation programmes similar analysis can be carried out with other values for the failure rate.

Failure rate, water demand and pipe roughness might have different characteristics from network to network and last but not least from country to country. Increasing pipe roughness and demand is not a problem in Norway, but problems with low velocity resulting from over-dimensioning. For networks in other regions of Europe this might not be the case.

6. Summary and conclusion

In summary, there exists a lot of possible ways of integrating failure forecasting and reliability into the long term planning tool. The existing approach in the *KANEW* framework can be improved. Based on experience from Norway applying the existing *KANEW*, some needs for improvements have also been discovered.

The following aspects related to development of the *Rehab Strategy Manager* in WP4 are important:

1. **Assessing survival functions (parameters) based on observed data**. Experience from Norway applying the existing *KANEW* program indicates that there is need for some type of validation of the parameters in ageing function (*Herz* distribution). By analysing observed maintenance data the possible range of the parameters can at least be limited.
2. **Improved pipe failure forecasting in WP4 at network level- link to WP2.** In the extended KANEW framework information about future failure development is needed. The existing approach is to assume a percentage increase in failure rate. This approach can be improved by using the models in WP2 or even a simple plotting technique.
3. **Reliability measure at network level suggested as an additional performance measure to be included in *Rehab Strategy Manager*.** Reliability of the network is not included as a measure in the existing KANEW framework. However, the reliability is an important issue to include also in long term planning.

The link between the failure forecasting models/reliability models and the long term forecasting tool is shown in Figure 7. By using the failure forecasting models and the reliability models in WP2, the input data to the *Rehab Strategy Manger* can be improved/extended and the results will be more reliable.

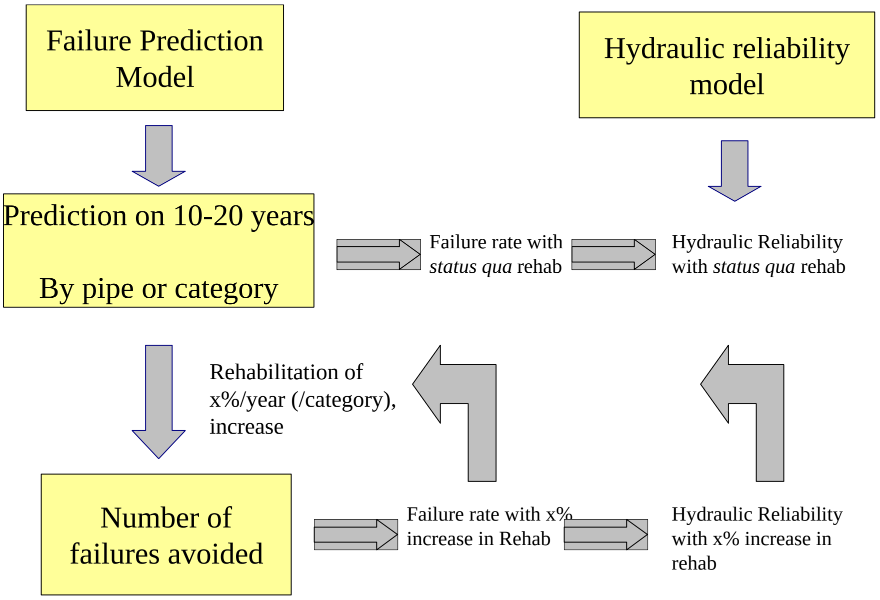


Figure 7. Linking between failure forecasting/reliability models and long term planning

7. References

Baptista, J.M. and Alegre, H. (2002). Construction of a Control Panel of Performance indicators for Rehabilitation: Validation of the rehab PI system, Report No. 2, CARE-W, Computer Aided Rehabilitation of Water networks, Lisbon.

6.3 Contribution of SINTEF

SINTEF REPORT

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TITLE

FAILURE RATE ANALYSIS IN REHABILITATED PIPES IN THE WATER NETWORKS OF TRONDHEIM AND OSLO

AUTHOR(S)

Anja Mattick and Sveinung Sægrov

CLIENT(S)

CARE-W Internal report

REPORT NO. STF66 A02089	CLASSIFICATION Unrestricted	CLIENTS REF.	
CLASS. THIS PAGE Unrestricted	ISBN 82-14-02688-1	PROJECT NO. 661280.04	NO. OF PAGES/APPENDICES 17 p.
ELECTRONIC FILE CODE s/6…661280/report/661280 Anja report on failures.doc		PROJECT MANAGER (NAME, SIGN.) Sveinung Sægrov	CHECKED BY (NAME, SIGN.) Frøydis Sjøvold
FILE CODE 6618/SS/BA	DATE 2002-08-14	APPROVED BY (NAME, POSITION, SIGN.) Herman Helness, Acting Research Director	

ABSTRACT

Knowledge about failure rates of pipes that have been rehabilitated is an important input to programs that aim to support the analysis of long-term rehabilitation needs. Two of the end-users of CARE-W, Trondheim and Oslo, have provided statistics from their previous practise. An efficiency factor for rehabilitation has been calculated for these two cities, relating the annual failure rate of rehabilitated pipes to the average failure rate in the year of rehabilitation

In Trondheim, about 50% of the rehabilitated network have been analysed. The results show that the average overall failure rate for the period 1988-2001 have been 0,28 failures/km/year, and there is no significant increase neither decrease during this period. No previous failure had been registered for 60% of the renovated pipes and 45% of the replaced pipes. The overall average failure rate for pipes when renovated are 2,1 failures/km year and replaced 2,4 failures/km year. The rehabilitation efficiency factor has steadily decreased since 1990, and the current value is approximately 5,0

In Oslo, for some casually selected rehabilitation projects the annual failure rate before renovation and replacement was 1,2 – 1,3 failures/km/year, whereas the average overall failure rate has been 0,14 failures/km/year and the accumulated failure is 3,3 failure/km over the registration period of 26 years. For some recently renovated pipe zones the rehabilitation efficiency ratio has been calculated to 4,4 and 8,3 respectively, while a site of replaced pipes had a rehabilitation efficiency factor of 13,1.

From these results, two main conclusions can be drawn:

1. Previous failures have only occurred for half of the rehabilitation projects. Still the level of failures is an important monitor for the overall network condition, and a connection between the failures and the need for rehabilitation should be established.
2. The previous failure rate tends to be slightly higher when pipes are being replaced compared to renovation projects. It also tends to be higher when single pipes are renovated compared to zone rehabilitation.
3. The efficiency of rehabilitation shows a decreasing trend. The worst cases were among the first ones to be rehabilitated.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Sanitary engineering	VA-teknikk
GROUP 2	Water distribution networks	Vannledningsnett
SELECTED BY AUTHOR	Rehabilitation needs	Rehabiliteringsbehov
	Forecasting	Prognoser
	Norway	Norge

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1 INTRODUCTION

1.1 Background

The overall objective of a water distribution system is to supply every customer permanently with enough water of good quality. A delivery stop can be disastrous, especially for producing industry and healthy institution, e.g. hospitals. In order to ensure reliable water distribution in the future, municipalities will during the next decades have to solve the problem of deteriorating water pipes. Deterioration may cause problems, e.g. reduced capacity of pipes due to increased failure rates. This makes it difficult to maintain the high level of water service, in terms of both quality and quantity. Maintenance is therefore becoming more and more important.

1.2 Project objective

The aim of this report is to analyse the water pipe network in Trondheim and Oslo for failure rates before renovating or replacing. Based on this analysis, a rehabilitation efficiency factor for Trondheim and Oslo has been defined. This factor relates the annual break rate of rehabilitated pipes to the average network break rate in the year of rehabilitation.

The GIS-programs Gemini VA and ArcView have been used for the analysis. Gemini VA is providing the failure and pipe data of the water network in Trondheim and Oslo, while Arc-View has been used for analysing and presenting the data and results for Trondheim.

2 FAILURE RATE ANALYSIS IN THE WATER NETWORK IN TRONDHEIM

2.1 The water network of Trondheim

The water pipe network in Trondheim consists of 8479 pipes with a total length of 749 km. Since 1988, when a complete failure statistic was made available, 3015 failures have occurred in the water network. The calculated average failure rate of the network is 0,28 /km/y (2001). Table 1 shows the development of pipe length and failure rate from 1988 until 2002.

Table 1: Network information Trondheim.

Year	No of pipes	Pipe length (km)	No of failures accumulated	Yearly failures	Failure rate (failure/km/year)
-1988	7837	682	0	0	0.00
-1989	8036	699	151	151	0.22
-1990	8236	714	341	190	0.27
-1991	8392	729	494	153	0.21
-1992	8499	739	721	227	0.31
-1993	8607	750	958	237	0.32
-1994	8745	761	1187	229	0.30
-1995	8899	778	1503	316	0.41
-1996	9015	786	1730	227	0.29
-1997	9154	800	1980	250	0.31
-1998	9293	811	2249	269	0.33
-1999	9409	821	2463	214	0.26
-2000	9456	825	2658	195	0.24
-2001	9518	832	2855	197	0.24
Average				**220**	**0,28**

Figure 1 shows the development of the failure rate from 1988 until today. In general for the whole period, there is no overriding tendency. However from one year to the next there are significant variations, due to climate conditions, leak detection projects etc.

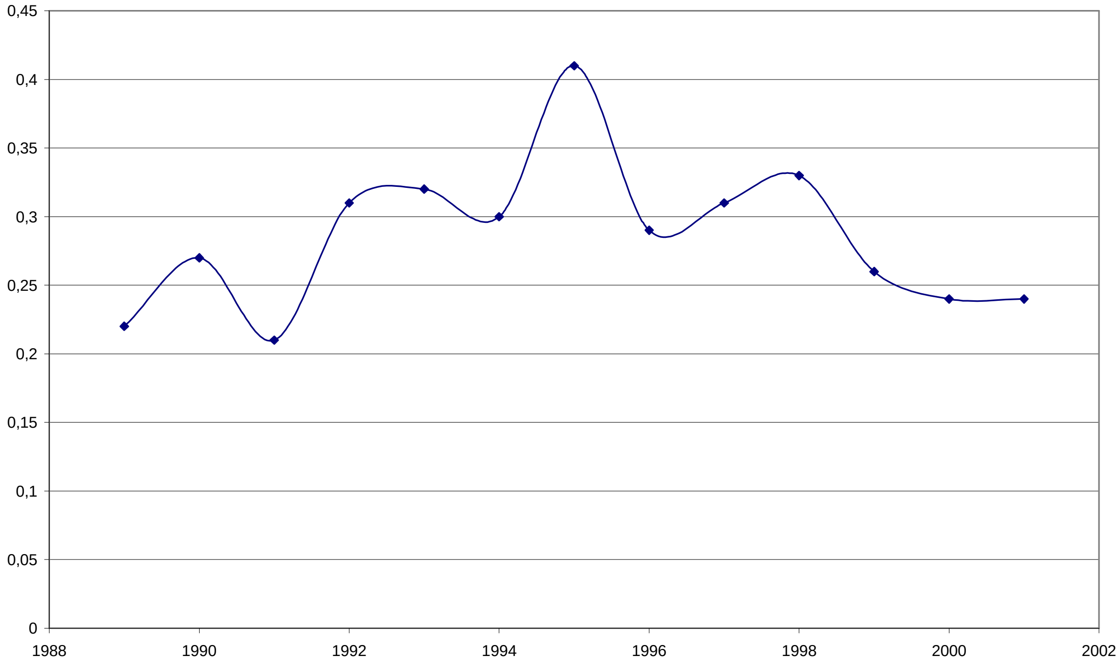

Figure 1: Failure rate development (failures pr km and year).

2.2 Rehabilitated pipes

Rehabilitated pipes can be divided in two groups, renovated and replaced pipes. Renovation of pipelines in general makes smaller impact on the surroundings compared to replacement. The mix of reasons of the rehabilitation action is probably different for these two groups. Therefore renovation and replacement have been analysed separately.

2.2.1 Renovated pipes

Renovation is a method of rehabilitation in which parts of the pipe are incorporated and its current performance improved. Until 2001 were 77 pipes renovated with a length of 6.03 km. In these pipes 69 breaks occurred. Table 2 summarises information of renovated pipes. Before 1988 few data has been registered. Data from 1988 to 1997 and to some extent more recent data have been analysed in this report. This is about 50% of the rehabilitated network. Further analysis might show a higher number of pipes that are rehabilitated without previous failures.

Table 2: Information of renovated pipes.

Year	Number of pipes renovated	Pipe length (km)	No of failures (accumulated since 1988 for the renovated pipes)	Accumulated failures/km	Accumulated failures/km number of registration years
-1988	9	0,62	0	0	0
-1989	3	0,32	0	0	0
-1990	8	0,89	11	12,4	4,1
-1991	7	0,58	1	1,7	0,4
-1992	8	0,68	5	7,4	1,5
-1993	11	0,91	18	19,8	3,3
-1994	8	0,66	10	15,2	2,2
-1995	7	0,44	15	34,1	4,3
-1996	3	0,31	9	29,0	3,3
-1997	10	0,52	0	17,1	1,7
Average	**7**	**0,59**	**7**	**13,7**	**2,1**

Figure 2 shows the pipe length distribution.

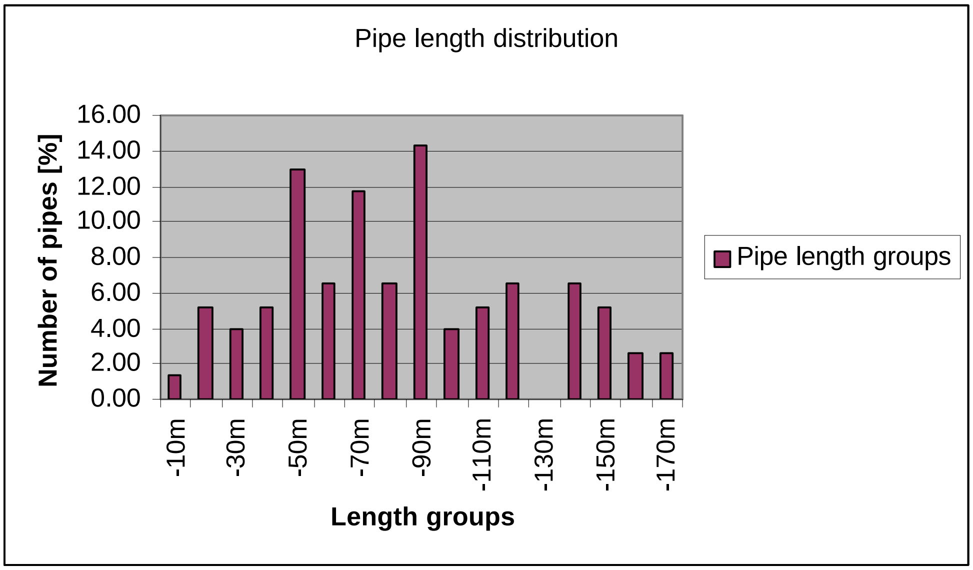

Figure 2: Pipe length distribution

Figure 3 shows renovated pipes (old Rehab) with project numbers. A ”project” in this term may include several close located pipes renovated at different times

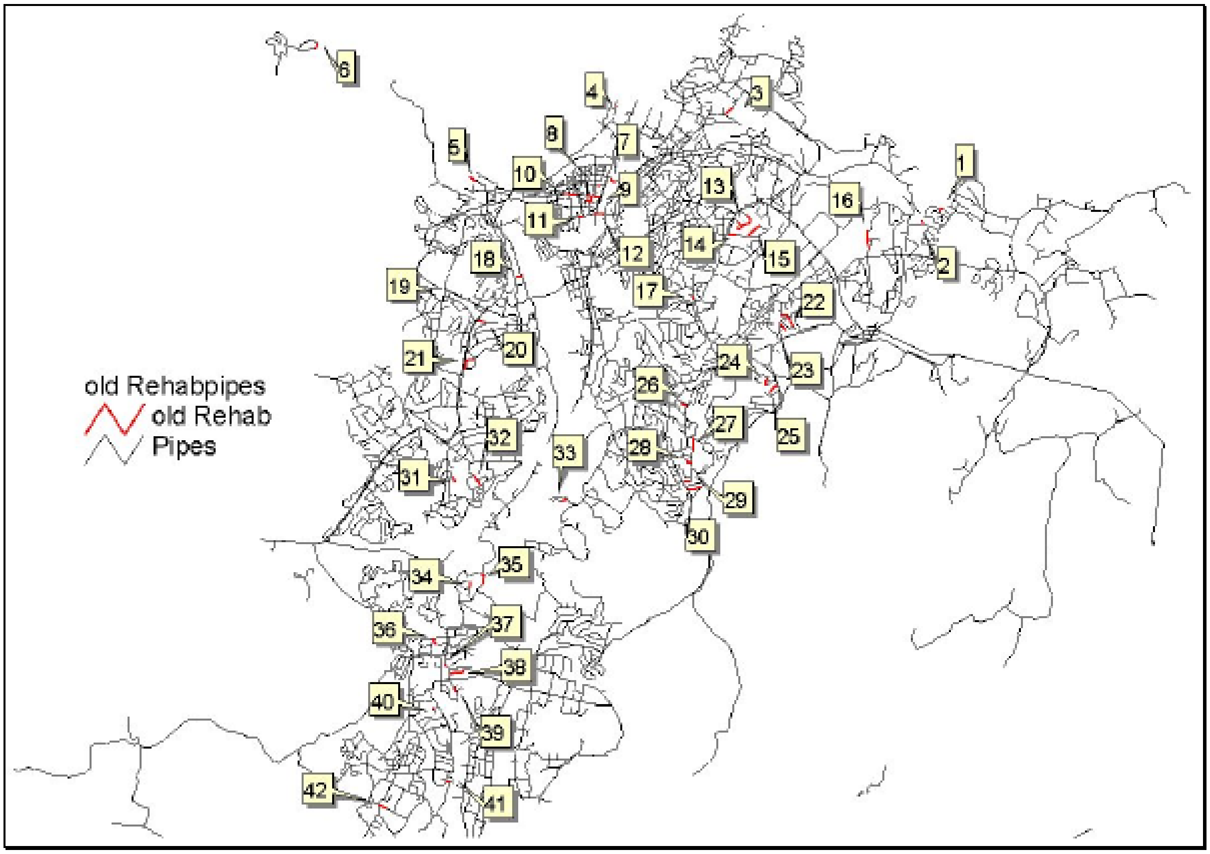

Figure 3: Renovated pipes in the water network Trondheim.

The analysis shows that no previous failures had occurred in 61 % of all renovated pipes before renovation took place, while one or more failures had occurred in 39% (Figure 4). The average failure rate of pipes with failures at the time of renovation is 2,1 failures/km/ year quite high, mainly caused by short pipe lengths. In most of the cases the failure rate is quite low and does not indicate a high need of rehabilitation. It can therefore be assumed that renovation mainly does not depend on high failure rates. The exact renovation reasons are not collected in the municipality Trondheim.

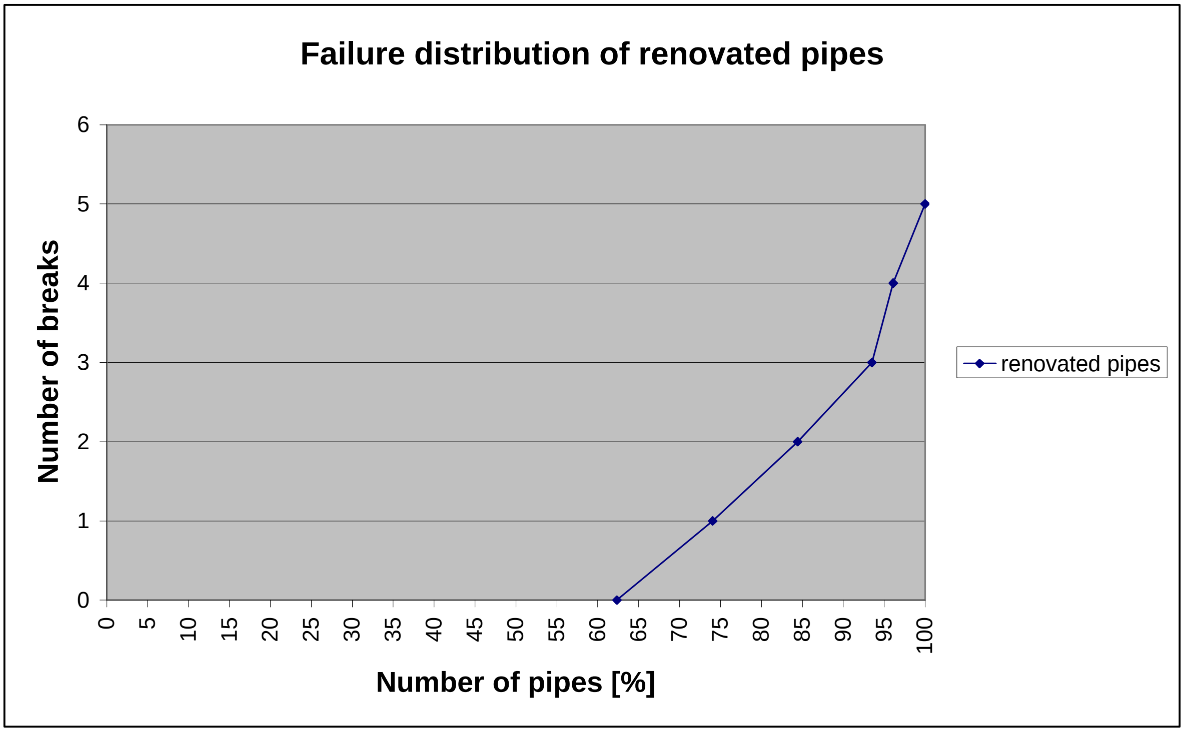

Figure 4: Failure distribution of renovated pipes.

2.2.2 Replaced pipes

Until 2002, 1052 pipes with a length of 84,67 km were replaced. From this material 482 pipes with a total length of 40,70 km has been analysed in this report. In these pipes 774 failures occurred prior to the replacement. Table 3 summarises information of replaced pipes.

Figure 5 shows the pipe length distribution and figure 6 the replaced pipes in the water network in Trondheim.

Table 3: Information of replaced pipes.

Year	Number of pipes replaced	Pipe length (m)	Number of failures before replacement (accumulated since 1988 for the replaced pipes)	Accumulated failures/km	Accumulated failures/km number of registration years)
-1988	15	1.49	0	0	0.00
-1989	4	0,35	2	5,7	2,9
-1990	20	1,53	28	19,6	6,5
-1991	31	3,18	25	7,9	2,0
-1992	12	0,90	11	13,3	2,7
-1993	36	2,77	63	23,1	3,9
-1994	58	5,68	89	15,8	2,3
-1995	39	3,28	54	16,5	2,1
-1996	48	3,39	70	20,6	2,3
-1997	47	2,86	41	14,3	1,4
-1998	40	2,94	82	27,9	2,5
-1999	48	3,55	112	31,5	2,6
-2000	25	2,21	60	27,1	2,1
-2001	35	4,60	65	14,1	1,0
Average	33	2,77	51	18,3	2,4

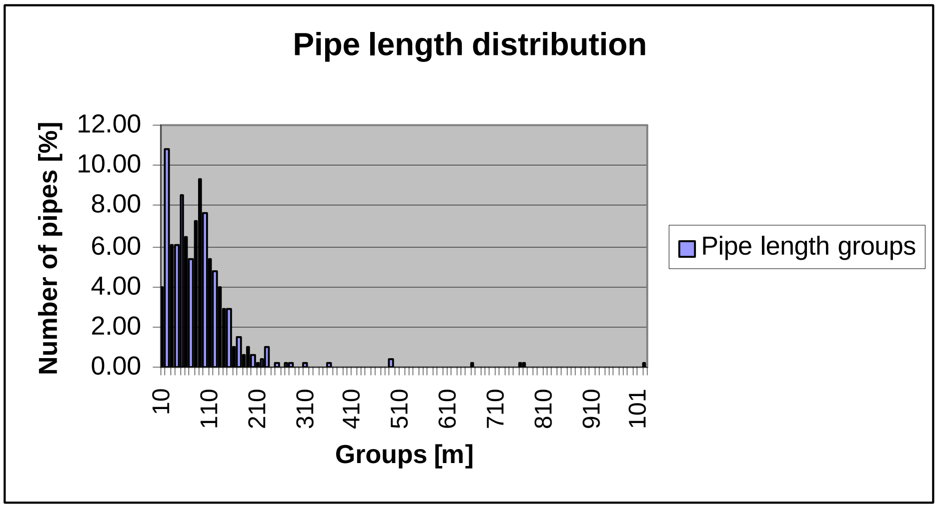

Figure 5: Pipe length distribution.

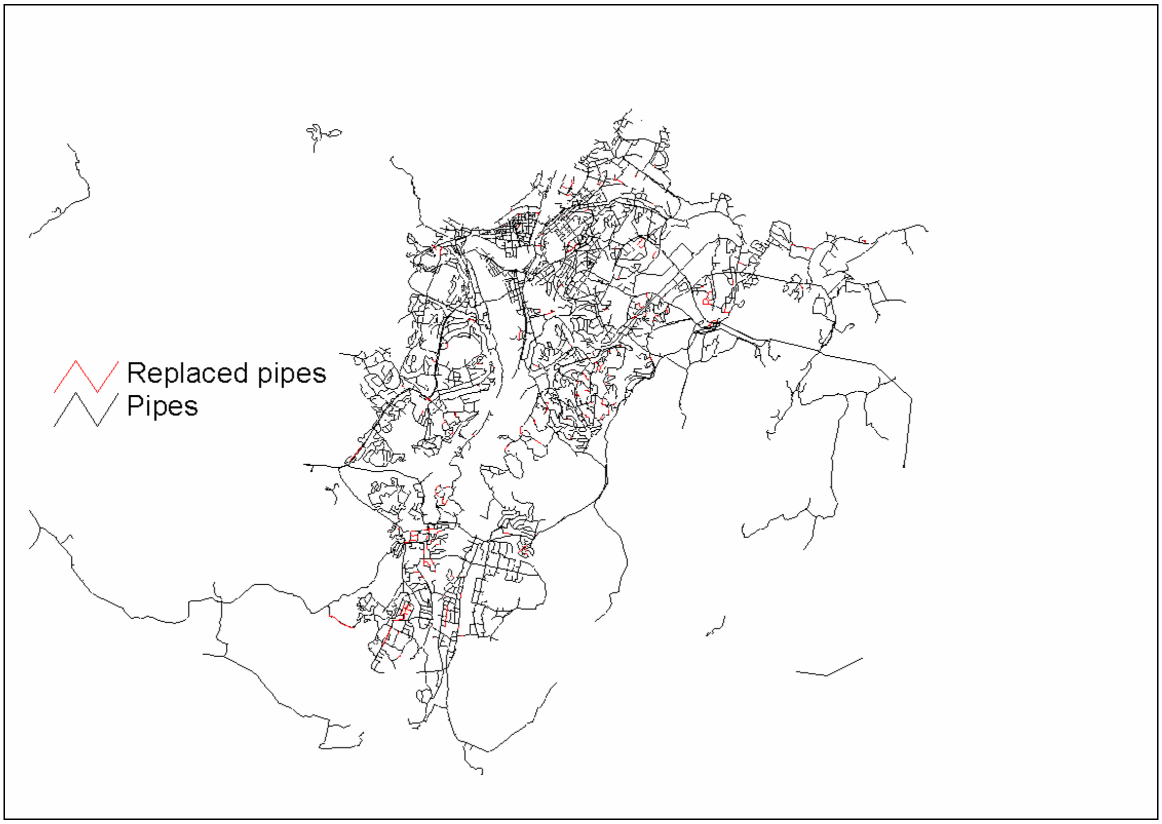

Figure 6: Replaced pipes in the water network Trondheim.

For each replaced pipe the failure rate at the time of replacing is calculated. The distribution of the failure amount for replaced pipes is shown in Figure 7. The calculated average failure rate for pipes with failures is 4.45 failures/km/y. The result might be influenced by short pipe lengths being rehabilitated and the short period of failure statistics. The exact replacing reasons are not recorded by the municipality in Trondheim and could therefore not be investigated. But it can be assumed that high failure intensity indicates replacing candidates.

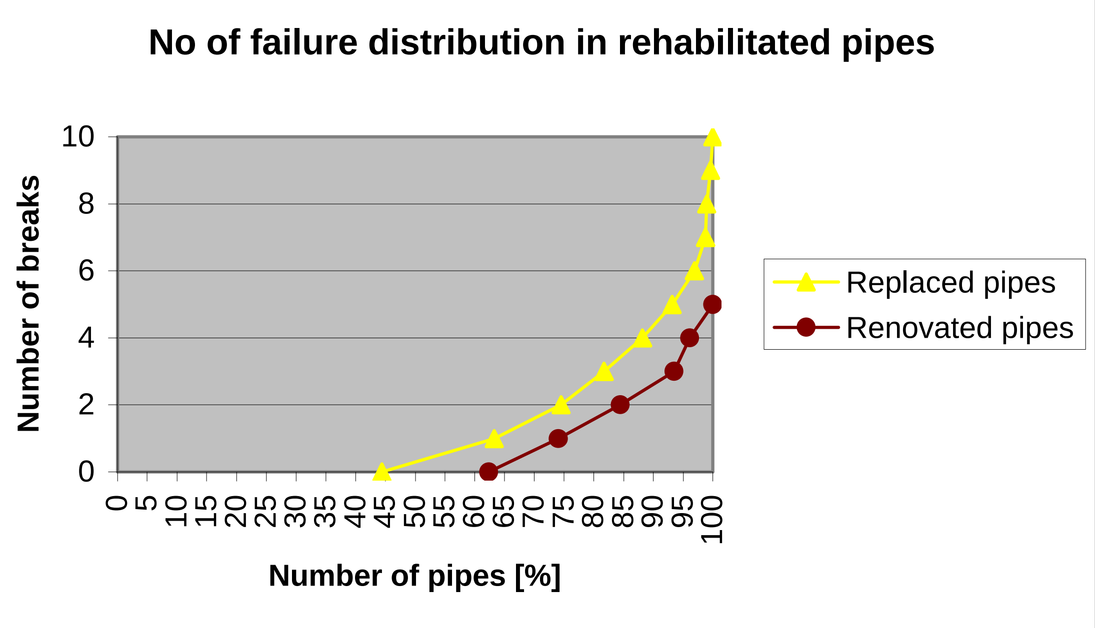

Figure 7: Number of failure distribution in rehabilitated pipes.

Evaluation of the rehab efficiency factor

The rehabilitation efficiency factor relates the annual failure rate of pipes before rehabilitation to the average network failure rate in the year of rehabilitation. The factor is calculated for renovated respectively replaced pipes, table 4 and figures 8 and 9. The rehab efficiency factor is about 50% higher for replaced pipes than renovated pipes. This means that pipes in a very bad condition is more likely to be replaced than renovated. The table and figures also show that the efficiency was highest during the first years of active rehabilitation, and has more or less stabilised at the last years of records at a level of 5 for renovated pipes and 7 for replaced pipes.

Table 4: Rehabilitation efficiency factor pr year in Trondheim.

Year	**Renovation efficiency factor**	
	Renovation	**Replacement**
-1988	0	0
-1989	0	13,2
-1990	11,1	24,1
-1991	7,9	9,5
-1992	4,5	8,7
-1993	5,5	12,2
-1994	5,4	7,7
-1995	4,1	5,1
-1996	5,5	7,9
-1997		4,5
-1998		7,6
-1999		10
-2000		8,8
-2001		4,2
Average	6,3	9,5

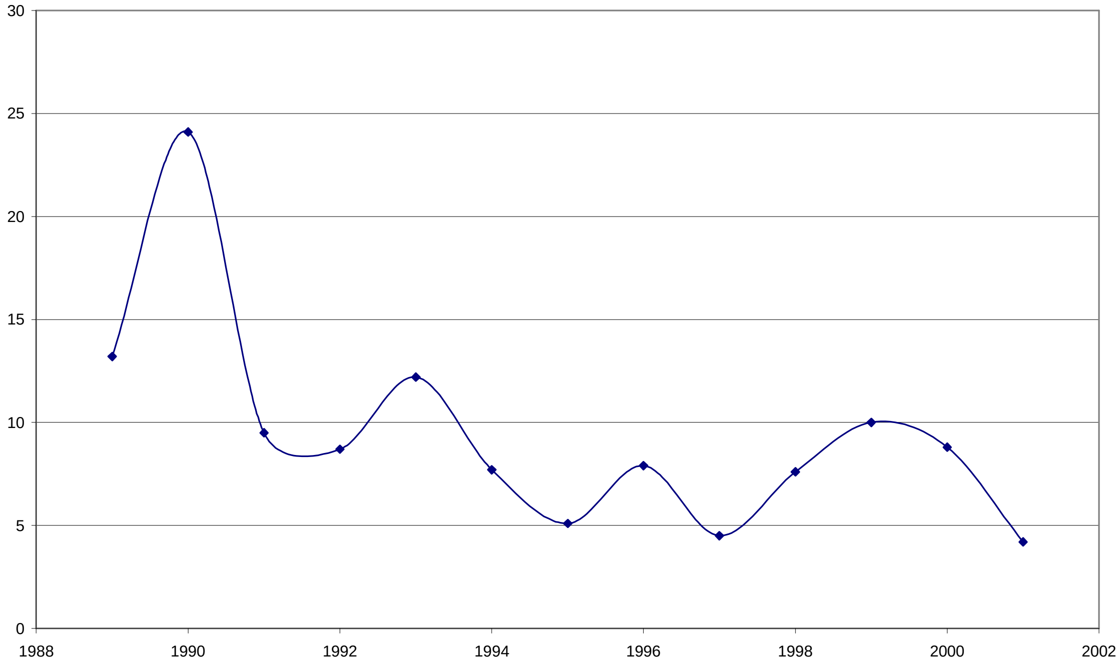

Figure 8: Development of the Rehab Efficiency Factor for Trondheim, replacement of pipelines

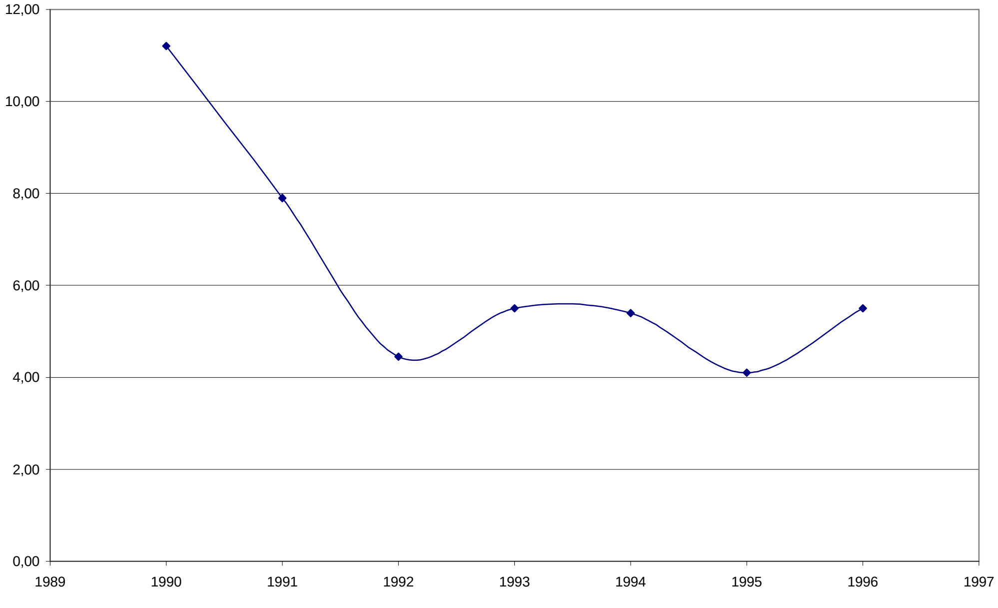

Figure 9 Development of the Rehab Efficiency Factor for Trondheim, renovation of pipelines.

3 FAILURE RATE ANALYSIS IN THE WATER NETWORK IN OSLO

The total length of the water network in Oslo is 1614 km by the end of 2001. In the period 1976-2001 a total number of 8045 failures were recorded The average failure rate in this period was 0,14 failures/km year, and the accumulated number of failures 3,3/km/26years. No significant trend for failure frequency has been observed during these 26 years. Table 5 and figure 10 shows the development of pipe length, failures and failure rate from 1976 until 2001.

Table 5 Failures in Oslo pr year.

Year	**Pipe length (km)**	**Number of failures**	**Number of failures accumulated**	**Failure rate (failure/km year**	**Failure rate accumulated**
1976	1322	205	205	0,16	0,16
1977	1334	215	420	0,16	0,32
1978	1346	210	630	0,16	0,48
1979	1353	269	909	0,20	0,68
1980	1381	222	1131	0,16	0,84
1981	1388	204	1335	0,15	0,99
1982	1403	193	1528	0,14	1,13
1983	1417	191	1719	0,13	1,26
1984	1426	195	1914	0,14	1,40
1985	1453	225	2139	0,15	1,55
1986	1469	238	2378	0,16	1,71
1987	1482	211	2589	0,14	1,85
1988	1497	135	2724	0,09	1,94
1989	1504	162	2886	0,11	2,05
1990	1513	129	3015	0,09	2,14
1991	1519	169	3184	0,11	2,25
1992	1526	166	3350	0,11	2,36
1993	1535	160	3510	0,10	2,46
1994	1544	234	3744	0,15	2,61
1995	1550	162	3906	0,10	2,71
1996	1557	360	4266	0,23	2,94
1997	1569	192	4458	0,12	3,06
1998	1582	271	4729	0,17	3,23
1999	1593	215	4944	0,13	3,36
2000	1605	195	5139	0,12	3,48
2001	1614	187	5326	0,14	3,62
Average		204		0,14	

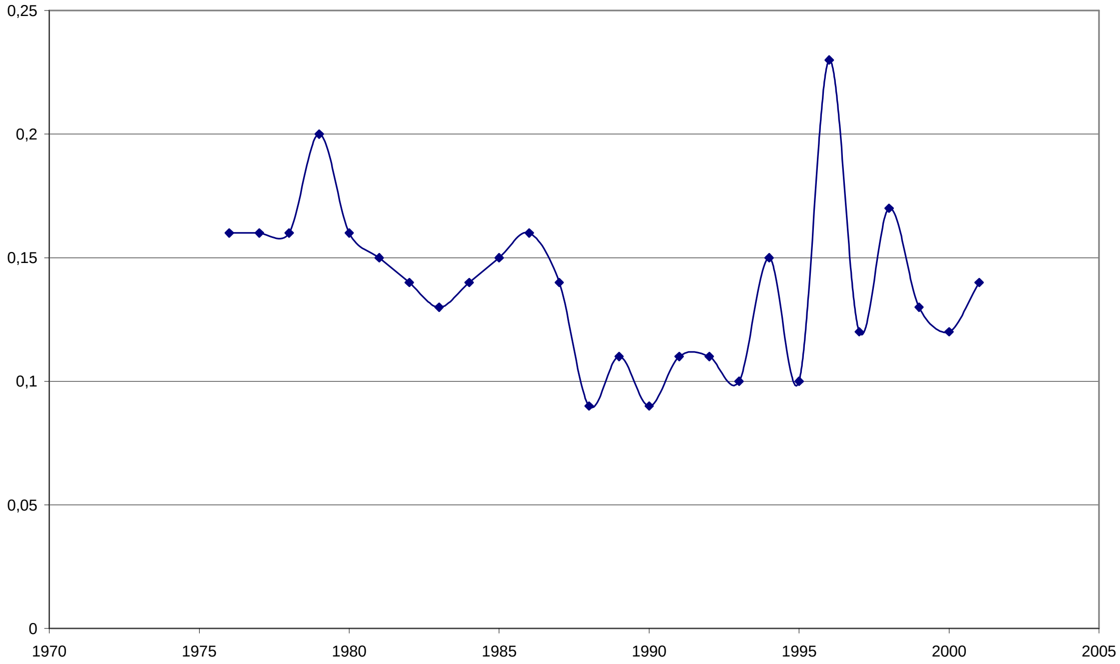

Figure 10 Failure rate development (failures pr km and year) in Oslo.

Three rehabilitation projects have recently been examined (2001), each of them representing a rehabilitation action for a particular zone. Some key figures are shown in the tables 6 and 7.

Table 6 Total length and total number of failures over 26 year for the rehabilitation sites.

Site	**Veitvedt renovation**		**Makrellbekken renovation**		**Makrellbekken replacement**	
Total length (m)	969		906		787	
Total number of failures/km	28,9		15,5		45,7	

Table 7 Failure frequency before rehabilitation in Oslo (failures/km year)

Site	Veitvedt renovation		Makrellbekken renovation		Makrellbekken replacement	
	No of failures/km and year	Accu-mulated failures/km	No of failures/ km and year	Accu-mulated failures/km	No of failures/ km and year	Accu-mulated failures/km
1976-1980	1,44	7,2	1,10	5,5	2,03	10,2
1981-1985	1,86	15,5	0	5,5	2,03	20,3
1986-1990	1,44	23,9	0,66	8,9	1,27	26,7
1991-1995	0,62	26,9	0,88	13,3	2,03	36,7
1996-2000	0,41	28,9	0,44	15,5	1,78	46,8
Average	1,16		0,62		1,83	

Table 8 Rehabilitation efficiency factor.

Site	Failure rate average 2001	Failure rate site	Rehab efficiency factor
Veitvedt renovation	0,14	1,16	8,3
Makrellbekken renovation	0,14	0,62	4,4
Makrellbeken replacement	0,14	1,83	13,1

4 CONCLUSION

Knowledge about failure rates of pipes that have been rehabilitated is an important input to programs that aim to support the analysis of long-term rehabilitation needs. Two of the end-users of CARE-W, Trondheim and Oslo, have provided statistics from their previous practise. An efficiency factor for rehabilitation has been calculated for these two cities, relating the annual failure rate of rehabilitated pipes to the average break rate in the year of rehabilitation.

Analysis of about 50% of the rehabilitated network in Trondheim shows that the average overall failure rate for the period 1988-2001 have been 0,28 failures pr km and year, and there is no significant increase neither decrease during this period. No previous failure had been registered for 60% of the renovated pipes and 45% of the replaced pipes. The overall average failure rate for renovated pipes are 2,1, and for replaced pipes 2,4. The corresponding rehabilitation efficiency factor is 6,3 for renovated pipes and 9,5 for replaced pipes. The efficiency factor was larger the first years after registration started. The average factor for the last five years of registration is 5,0 for renovated pipes and 7,0 for replaced pipes.

In Oslo, the annual failure rate has been calculated for some casually selected rehabilitation projects. The failure rate before renovation and replacement was 1,2 – 1,3 failures/km year, whereas the average overall failure rate has been 0,14 failures pr km and year and the accumulated failure is 3,3 failure/km over the registration period of 26 years. For some recently renovated pipe zones the rehab efficiency ratio has been calculated to 4,4 and 8,3 respectively, while a site of replaced pipes had a rehabilitation efficiency factor of 13,1.

From these results, two main conclusions can be drawn:

1. Previous failures had only occurred for half of the pipelines that have been rehabilitated. Still the level of failures is an important monitor for the overall network condition, and a connection between the failures and the need for rehabilitation should be established.

2. The previous failure rate tends to be slightly higher when pipes are being replaced compared to renovation projects. It also tends to be higher when single pipes are renovated compared to zone rehabilitation.

3. The rehabilitation efficiency rate has stabilised on a significantly lower level compared to the first years of systematic rehabilitation actions. This means that the worst pipes were rehabilitatad first. The renovated pipelines in general had five times higher a failure frequency compared to the average level. The corresponding number for replaced pipes was seven. Since the global average failure frequency in Oslo is lower than in Trondheim, the efficiency factor in Oslo show higher values.

6.4 Contribution of WRc

COMPUTER AIDED REHABILITATION OF WATER NETWORKS

RESEARCH AND TECHNOLOGICAL DEVELOPMENT PROJECT OF EUROPEAN COMMUNITY

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CARE – W

Computer Aided REhabilitation of Water Networks.
Decision Support Tools for Sustainable Water Network Management

WP4 – Strategic Planning and Investment

Task 2: Developing a Rehabilitation Scenario Manager

Pipeline Failure Rates – Contribution from WRc

1. Introduction

The aim of this paper is to provide input to Task 2 of Work Package 4. The objective of Task 2 is to develop the Rehabilitation Scenario Manager, which will forecast the rehabilitation needs of a network and the effects of rehabilitation activities carried out at specific times.

Further information is required on the relationship between the failure rates of specific pipelines at the time they were rehabilitated and the failure rate of the network as a whole. This information will be incorporated into the Rehabilitation Scenario Manager as a factor linking the behaviour of individual pipes to that of an entire network.

WRc has based the contents of this paper on both our experience of the rehabilitation practices adopted in the UK and on recent analysis of burst data from a number of UK water utilities (End Users).

2. Trigger Values For Rehabilitation

In the UK the structural condition of distribution mains is one of a number of parameters which would be examined as part of a rehabilitation planning exercise. The burst and failure rates of distribution mains within a zone would be analysed as part of a wider performance assessment. Other parameters would include water quality, pressure, interruptions to supply and leakage. Of these parameters, water quality has been the major driving factor behind rehabilitation in the UK in the past 10 to 15 years.

UK water utilities have different policies regarding the failure rates of pipelines which would trigger structural replacement. There is little publicly available documented evidence on the values which would trigger rehabilitation, this has often been determined from the knowledge and experience of the rehabilitation planning team.

UK water utilities are moving towards a more integrated method for assessing whether mains require rehabilitation and by which method. Burst and failure rates now tend to have a 'softer' role in rehabilitation planning, being one of a suite of parameters used to rank the performance of specific network zones.

An example of this is given in 'Integrated Network Rehabilitation Strategy – Work Procedures and Methodology'[1] produced by South West Water Ltd (SWWL). The rehabilitation strategy set out in this document states that the asset condition is one of the performance measures that is used to prioritise zones for rehabilitation. Table 1 below shows the failure rates that are used to score the structural performance of a zone. This score would be incorporated into an overall ranking of the performance of each zone.

Table 1 Weighting values for distribution mains

Type	Performance Bands	Score
Mains Failure	> 2.00 repairs per km of DMA mains	5
	> 1.00 repairs per km of DMA mains	4
	> 0.75 repairs per km of DMA mains	3
	> 0.50 repairs per km of DMA mains	2
	> 0.20 repairs per km of DMA mains	1
Service Pipe Failure	> 2.00 repairs per km of DMA service pipe	5
	> 1.00 repairs per km of DMA service pipe	4
	> 0.75 repairs per km of DMA service pipe	3
	> 0.50 repairs per km of DMA service pipe	2
	> 0.20 repairs per km of DMA service pipe	1
Note: The km lengths above refer to the entire distribution length in the study areas		

The scores would be based on 5 years worth of historical burst data.

Once zones have been identified for rehabilitation further detailed investigations would be carried out to determine the method of rehabilitation, i.e. structural or non-structural renovation. Technique selection would be based on whole life costing analysis tools, WATERFOWL in particular. The burst history of pipes within a zone would be used to target further investigation into the structural condition of the distribution mains within a supply zone.

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[1] 'South West Water Ltd Water Mains Rehabilitation. Integrated Network Rehabilitation Strategy – Work Procedures and Methodology', May 2002, Faber Maunsell.

WRc have had discussions with a number of other water utilities regarding the rules that govern mains replacement planning. All utilities responded that they adopt procedures similar to that described above. Therefore repair rate is only one of a number of performance indicators considered when prioritising mains for rehabilitation. A number of “rule of thumb” values historically used to trigger mains replacement were given. Threshold values ranging from **3 bursts per km over a five year period** to **5 bursts per km per year** were suggested. These cover such a wide range as to be of limited use.

The following section examines the actual failure rates of distribution mains in specific zones where rehabilitation work was going to be undertaken and compares them to the number of yearly bursts reported by individual water utilities in the UK.

3. Comparison of Failure Rates

3.1 Failure Rate For Specific Zones

Each water utility in the UK is required to report the number of bursts to Ofwat as part of a yearly summary of company activities. Burst data can be found in Table 11 (non-financial measures, water main activities) of the Annual Returns. The definition of a mains bursts in the Annual Returns is as follows:

> *'Mains bursts include all physical repair work from which water is lost which is attributable to pipes, fittings or joint material failures or movement, or caused or deemed to be caused by conditions or original pipe laying or subsequent changes in ground conditions…..Include ferrule failure which are attributable to mains material condition or local ground movement…*
>
> *For the avoidance of doubt, all leakage occurring at locations or through joint or material failures which would have been designed for the life of the main…should be regarded as mains bursts.'*

These values are available in the public domain and have been used as the company average mains failure rate for comparison with zonal information. Values reported for 1998-99 for the larger utilities are shown in Figure 1 below.

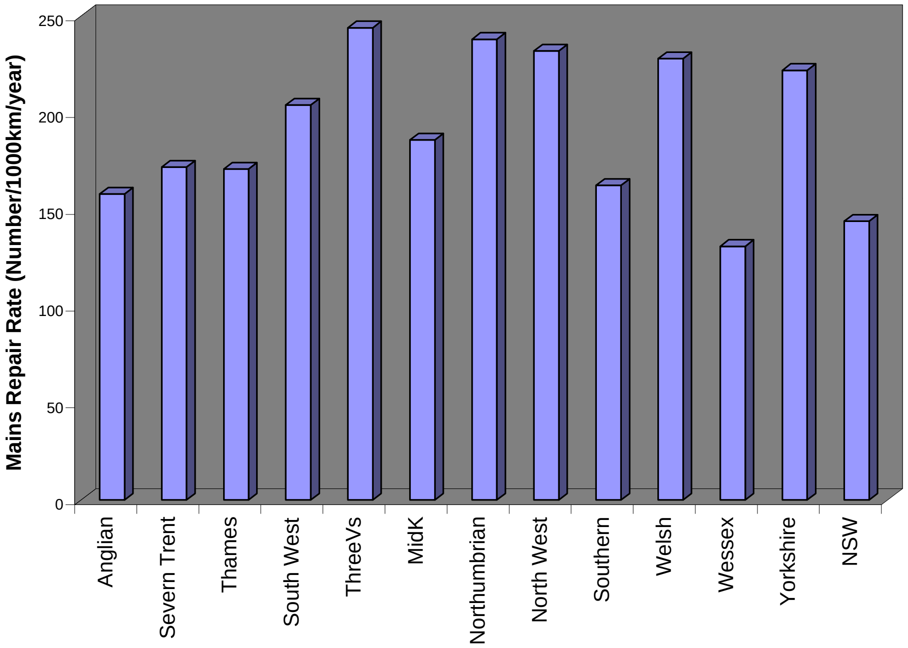

Figure 1 Reported Mains Failures for 1998-99

It can be seen that company average values varied from approximately 0.13 to 0.24 mains bursts per km in 1998-99, with the average being slightly higher than 0.19 per km.

The information contained in this section is taken from a 12 month study undertaken by WRc for a number of UK water utilities[2]. Here repair rates have been calculated before and after rehabilitation was carried out at specific district meter areas (DMAs).

The failure rates have been calculated for specific DMAs or zones. In the UK a DMA consists of between 500 and 3000 domestic properties and 5 to 30 km of distribution mains. The failure rates have been calculated from the number of repairs carried out on the distribution mains within each DMA. This includes mains, mains fittings and ferrules[3]. The rate has been calculated for the total length of distribution main within the DMA.

DMA repair information has been taken from the “work management systems” of individual water utilities. These works management systems keep an electronic record of all work undertaken on the whole of the water utility’s distribution network. Leakage and bursts repairs would be one of a number of activities recorded on these systems. The water utilities that have supplied information for this study do not currently link their works management records to GIS of the distribution network. The mains to which each individual repair was associated was therefore not automatically known. It has been necessary to carry out a great deal of data handling to ensure that the correct repair information has been analysed.

Table 2 below summarises the details of the DMAs included in this comparison exercise, giving the sizes of the DMAs and the proportions of distribution mains that have been rehabilitated. Only DMAs with 40% or more of their pipe lengths rehabilitated were included.

Table 2 DMA Details

Zone	No of properties	Length of distribution main	% rehabilitated	Primary rehabilitation technique
DMA1	1021	11.23 km	58%	Epoxy resin lining
DMA2	1153	11.633 km	44%	Epoxy resin lining
DMA3	824	8.211 km	40%	Replacement with PE
DMA4	1235	7.2 km	44%	Mixture of epoxy resin lining and replacement
DMA5	2005	30.036 km	87%	Mixture of epoxy resin lining and replacement
DMA6	1140	25.5 km	62%	Mixture of epoxy resin lining and replacement
DMA7	1023	13.864	93%	Replacement with PE

For each DMA the overall mains failure rate has been calculated, i.e. the total number of repairs divided by the total length of main in the DMA. This failure rate has been calculated for the year immediately before the rehabilitation work was due to be carried out. These values are presented in Table 3 below. This rate has been compared to the water utility burst rate for the same year, as reported in the Annual Returns. The ratio of the DMA failure rate to the water utility average failure rate has also been presented.

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[2] WRc Portfolio Research Project CP012: Maximising the Benefits of Water Mains Rehabilitation. This project is due to be completed in July 2002.

[3] A Ferrule is the connection of the service pipe to the main.

Table 3 Comparison of DMA to Water Utility Average Failure Rates

Zone	Mains# Failure Rate (per km per year)	Water Utility Average# Failure Rate (per km per year)	Ratio of DMA to Water Utility Average
DMA1	0.712	0.299	2.4
DMA2	0.628	0.299	2.1
DMA3	1.096	0.229	4.8
DMA4	0.139	0.208	0.7
DMA5	0.100	0.132	0.8
DMA6	0.118	0.132	0.9
DMA7	0.216	0.216	1.0
		Average	1.8
Note: #. Includes mains, mains fittings and ferrules			

At the DMA level there is a split between those DMAs which have a higher repair rate than the water utility average and those which have a lower repair rate. The repair rates vary from 4.8 to 2.1 times higher than the utility average to between 0.7 and 0.9 times lower. **On average, the DMAs which are due to be rehabilitated have a mains repair rate 1.8 times greater than the water utility as a whole.**

The failure rates given in Table 3 are for the whole of the DMA. Within each of these DMAs the exact location of the repairs is known, as discussed previously. It is therefore possible to determine whether the repairs were carried out to those mains which were due to be rehabilitated or to those that would not be included in the rehabilitation work. DMA repair rates have therefore been determined solely based on the repairs carried out to those mains due to be rehabilitated. Again, the failure rates have been calculated for the year prior to the rehabilitation work being undertaken. This information is presented in Table 4.

Table 4 Comparison of Mains Due to be Rehabilitated and Water Utility Average

Zone	Failure rate for mains due to be rehabilitated (per km per year)	Company Burst Rate (per km per year)	Ratio of DMA to Water Utility Average
DMA1	1.266	0.299	4.2
DMA2	0.645	0.299	2.2
DMA3	0.903	0.229	3.9
DMA4	0.442	0.208	2.1
DMA5	0.290	0.132	2.2
DMA6	0.211	0.132	1.6
DMA7	0.275	0.216	1.3
		Average	2.5

In all cases the failure rate of the mains to be rehabilitated are higher than the overall utility failure rates over the same period. **On average, the mains due to be rehabilitated had a failure rate 2.5 times higher than the water utility average failure rate**.

The actual failure rates of the mains due to be rehabilitated (Table 4, column 2) varies between 1.266 and 0.211 repairs per km per year. When these are compared to the typical trigger levels discussed in Section 2 it can be seen that these repair rates alone would not have initiated rehabilitation of the water mains. In fact, in all cases the rehabilitation work was carried out to improve water quality issues associated with unlined cast iron (CI) mains. The structural condition of the asset would not have been the main driver for the rehabilitation of these DMAs. When comparing all DMAs, as the amount of planned rehabilitation increases in general the mains failure rate prior to rehabilitation decreases (Figure 2 below). This relationship emphasises that the rehabilitation has not been driven mainly by mains failure rate. Indeed, the use of epoxy resin lining for some of the DMAs suggests repair rates which were acceptable to the utility.

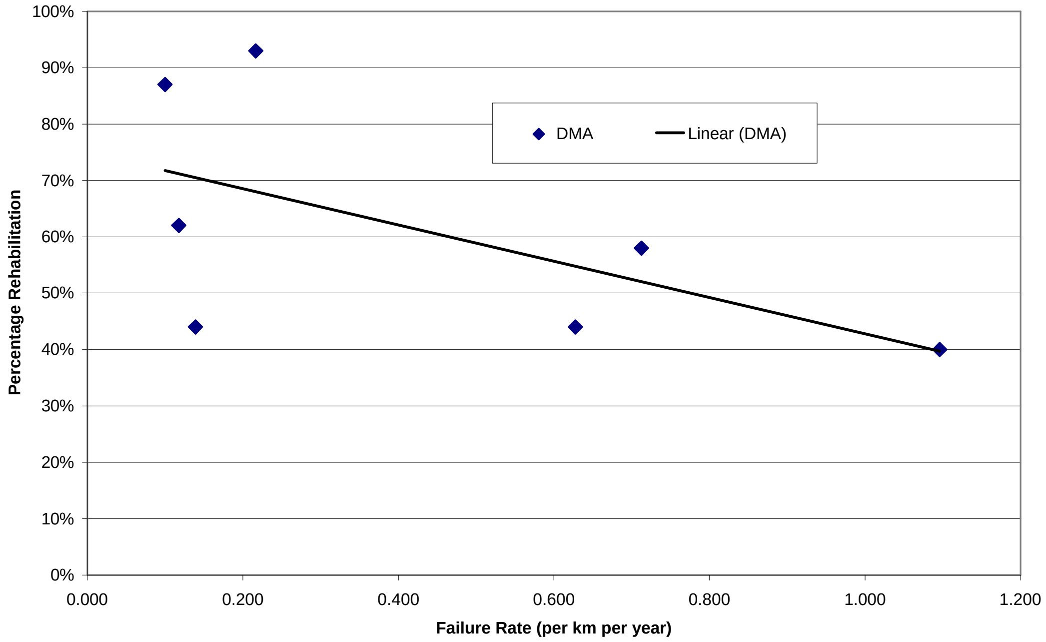

Figure 2 Percentage Rehabilitation v Failure Rate

When the DMA failure rates for one water utility are plotted against the proportion of the DMA which is due to be replaced, it can be seen that the repair rate increases as the percentage replacement increases (Figure 3). This relationship would be expected, i.e. as the failure rate increases then the amount of main needing replacement would increase. However, this trend is not evident when comparing all the data. Again this is due to reasons behind the rehabilitation work and also because rehabilitation policies will vary between individual water utilities.

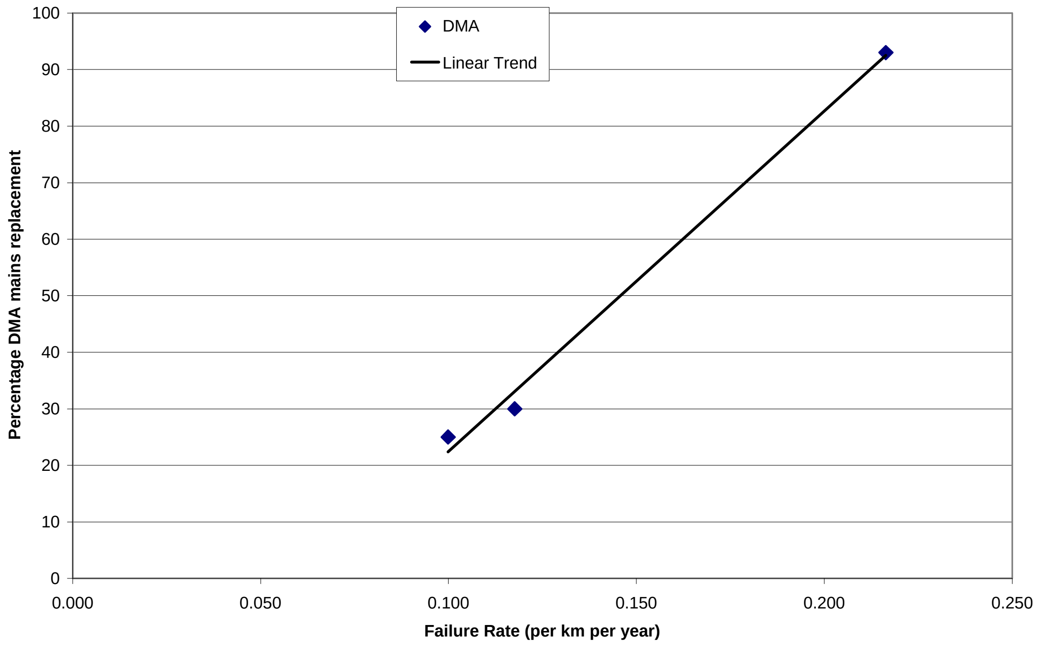

Figure 3 **Percentage Replaced v Failure Rate in DMA for One Utility**

The relationship between failure rates and the rehabilitation strategies applied to these seven DMAs is not straightforward. Individual water utilities have different policies for rehabilitation. The choice of rehabilitation techniques may even vary between regions within one water utility. For instance, epoxy resin lining would have been the preferred rehabilitation option to alleviate water quality problems for one of the water utilities included in this study. The decision to use replacement techniques in place of lining would have been influenced by practical constraints such as the number and density of service connections, particularly lead or galvanised iron.

3.2 Failure Rates by Rehabilitation Method

Only scrape & lining was carried out in 2 of the seven DMAs in Table 3, replacement was only done in another 2 of these with both rehabilitation methods used in the other 3DMAs. Additional data were available from 2 further DMAs where a small percentage (less than 25% of the DMAs) of scrape and lining had been carried out. As repairs have been allocated against individual pipe lengths, it was possible to calculate burst rates pre and post rehabilitation by method used. Data were available for approximately three years before and after rehabilitation. Additionally the repair rates for the pipes not rehabilitated could also be monitored over this period. Values are given in Table 5 in and displayed in Figure 4 below. For scrape and lining values are presented for the mains including ferrules and main fittings and for the mains alone. This was done as there was an unusually high number of repairs on mains fittings prior to rehabilitation for scrape and lined pipes.

Table 5 Repair Rates Before and After Rehabilitation by Method

	Rehabilitation Method			
	Replacement	**No Rehab**	**Scrape & Line**	**Scrape & Line Mains Only**
Pre Rehabilitation	0.25	0.23	0.25	0.14
Post Rehabilitation	0.18	0.27	0.34	0.27

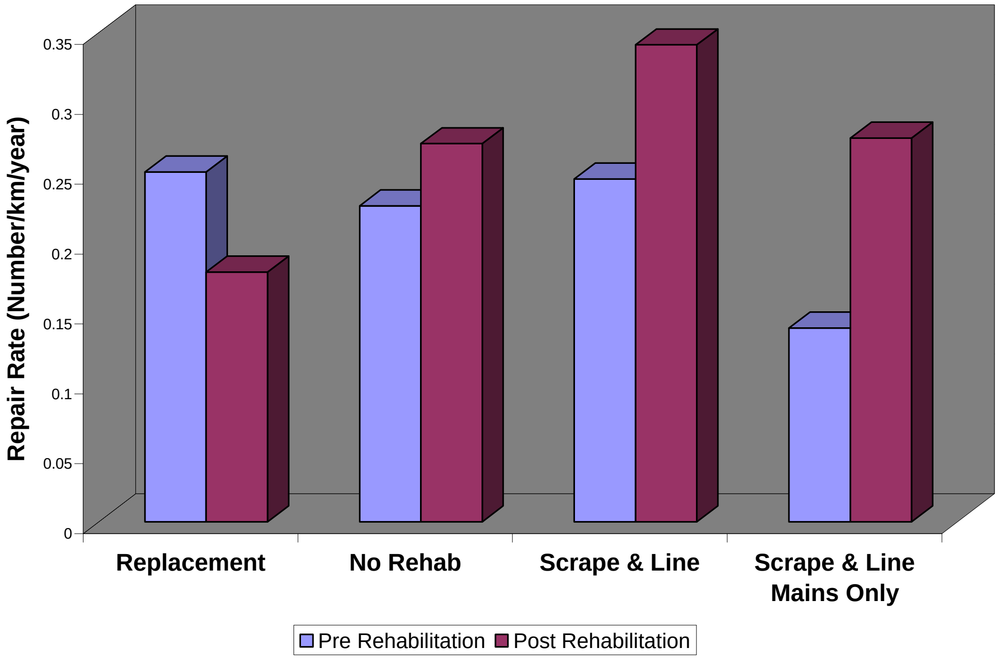

Figure 4 Repair Rates Before and After Rehabilitation by Method

Again it is evident that the pre-rehabilitation values are not excessive when compared against the utility average rates in Figure 1.

However it is also evident that on average repairs reduced after replacement and increased after scrape and lining. The increase in the latter is thought to be associated with disruption caused during the cleaning process.

There is evidence of an increase in the repair rates of non-rehabilitated mains over the same time period although this is less than the differences for the other (rehabilitation) methods.

These results are in keeping with trends found from analysing other companies' data. In WRc's experience rates below 0.1 repairs/km/year are not uncommon after mains replacement.

3.3 Failure Rates for Specific Pipeline Types

The final part of this analysis is to compare the failure rates for pipelines of specific diameters and materials with the overall network failure rates.

The information in this section has been provided by one UK End User and is based on the historical mains burst records for their entire network. Failure rates have been calculated for CI pipes that have either been lined with epoxy resin or sliplined with

PE. The rehabilitation work for these CI pipes was carried out during 2000, and the failure rates have been calculated for the five years prior to rehabilitation.

Due to the amount of data available three categories of pipes have been selected, as follows:

- 100mm CI mains lined with epoxy resin in 2000;
- 80mm CI mains lined with epoxy resin in 2000, and;
- 80mm CI mains sliplined in 2000.

Table 6 below shows the yearly failure rate for each category of pipeline, for the five years prior to the rehabilitation work. The failure rate is based on the number of bursts each year on the length of main due to be rehabilitated in 2000. This failure rate has been compared to the number of mains bursts reported to Ofwat by the water utility for the same period. This is the same value as discussed in Section 3.1 above.

Table 6 Comparison of Mains Failure Rates with Network (Utility Average) Failure Rates

Year	**Mains Failure rate (per km per year)**			**Reported Network Failure Rate (per km per year)**
	100mm epoxy lined CI mains	**80mm epoxy lined CI mains**	**80mm sliplined CI mains**	
1995	0.09	0.36	2.89	0.276
1996	0.17	0.46	0.58	0.247
1997	0.35	0.26	0.58	0.157
1998	0.17	0.15	0	0.134
1999	0.17	0.05	0	0.144
5yr Ave	**0.19**	**0.256**	**0.81**	**0.192**

As can be seen from Table 6, the failure rates of the different categories of pipe do vary. As you would expect, the cast iron pipes which will be epoxy lined generally have a much lower failure rate than those due to be replaced. It is interesting to note that although the failure rates on the sliplined mains are greater on average than the epoxy lined mains, they are below the typical trigger values given in Section 2. This is again a reflection of the fact that water quality has been the main driver behind the rehabilitation work undertaken in the UK. Sliplining would have been selected for other reasons such as density of service connects or cost. Alternatively, poor structural condition (despite an acceptable burst rate) may have triggered replacement.

Table 7 Ratio of Pipeline and Network (Utility Average) Failure Rates

Year	**Ratio of Pipe and Network Failure Rate**		
	100mm epoxy lined CI mains	**80mm epoxy lined CI mains**	**80mm sliplined CI mains**
1995	0.3	1.3	10.5
1996	0.7	1.9	2.3
1997	2.2	1.7	3.7
1998	1.3	1.1	0
1999	1.2	0.3	0
5 Year Ave	**1.1**	**1.3**	**3.3**

Table 7 above shows the amount by which the pipe category failure rate differs from the network failure rate, for the same year as a ratio to the company average value. With a few exceptions, the failure rates for the specific categories of main are greater than those reported for the whole network. The CI pipes due to be sliplined have a failure rate up to 10.5 times greater than the network average. There were no reported bursts on the mains during the two years prior to the rehabilitation work being carried out. **Over the 5 year period the burst rate was 3.3 times higher than the company level values on average**.

For the CI pipes due to be epoxy lined the failure rates vary from 2.2 times greater to a third lower than for the entire network. **Over the five year period the burst rates were not significantly different from the company level values on average**. Again, epoxy lining would have been selected because these mains would have been experiencing water quality problems, not because they were subject to excessive structural failure.

4. Summary

Various burst rate levels are used in the UK to trigger mains rehabilitation. However, repair rates have played less of a role in rehabilitation planning than water quality in recent years.

Reported utility level burst rates on water mains varied between 0.13 and 0.24/km/year for 1998-99.

The analysis of burst data for a number of UK water utility demonstrates that the failure rates of specific rehabilitated zones, prior to the rehabilitation work, were on average 1.8 times higher than for the water utility as a whole. Pipes specifically targeted for rehabilitation within the DMAs had burst rates which were on average 2.5 times higher than for the water utility as a whole.

The failure rates for a number of pipe categories have also been shown to be greater than those of the whole network. For mains due to be replaced the failure rate was 3.3 times higher than the company level values on average over a five year period. Over the same time period, pipes due to be scraped and lined had burst rates not significantly different to company average values.

There is evidence of burst rates increasing after scrape and lining, possibly due to disruption caused during the cleaning process.

The calculated failure rates of the mains due to be replaced were lower than the typical trigger values suggested by UK water utilities. This is a reflection of the fact that mains rehabilitation in the UK has been driven by water quality rather than structural performance.

Reductions in burst rates after replacement were observed. An average value of 0.18 repairs per km per year post replacement was calculated from data supplied by companies supporting the CARE-W project. The post rehabilitation differences observed are in keeping with trends found from analysing other companies' data. In WRc's experience rates below 0.1 repairs/km/year are not uncommon after mains replacement.

6.5 Contribution of BUT

COMPUTER AIDED REHABILITATION OF WATER NETWORKS
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CARE – W

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

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WP4 – Strategic planning and investment

Report on failures analysis of the Brno water distribution network

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Brno, July 2002

INTRODUCTION

The case study on the analysis of failures is based on data from our end-user Brno Waterworks and Sewers (BVK, a.s.). In the beginning we encountered a problem concerning the way the data are stored. There are two databases available. One is related to the GIS system and gives complete information on water mains (i.e. pipe section ID, its length, type of material, profile, name of the street, date of installation, rehab date, rehab technology etc.) The other one comprises information on failures (type of failure, date, street and profile) since 1994. Before that year failure data were registered on papers only, which is not applicable. These two databases are not interconnected and we do not know, on which pipe section (of what type of material, age, length etc.) the failure occurred. The only way to solve this problem is to locate each failure and to assign it to the relevant pipe section manually. We have done this assignment on the two pressure zones of the Brno water distribution system (Chrlice and Barvicova), that had been chosen for testing in WP3. Now we are working on a detailed analysis of water mains failures there.

This report is divided into two parts. In the first one there are basic information on the water distribution network operated by BVK, a.s. The second one contains information on mains failures.

1. BASIC INFORMATION ON THE WATER DISTRIBUTION NETWORK

On the date of December 31, 2001 Brno Waterworks and Sewers operated and managed as many as 1166 km of water distribution network. For the structure of the network according to the type of material and age see tab.1 and fig.1.

As you can see in the table and chart, the Brno water supply network consists mainly of grey cast iron pipes that makes up 69,4 % of all pipes. There are 12,4 % of ductile iron and 11,3 % of steel pipes. Other materials are less than 4,0 % of all pipes.

Regarding the age of pipes, the oldest registered pipes are from 1872. Until 1944 the only material used for water pipeline was grey cast iron. 33,8 % of all grey cast iron pipes were installed before 1950, so they are more than 50 years old.

Tab. 1: *Water mains material and age*

MAINS LENGTH [m]								updated: December 31, 2001	
	MAINS MATERIALS								
MAINS AGE	GG	GGG	PE	PVC	STEEL	GRP	AC	unknown	TOTAL
<1900	4 383								4 383
1900-1904	4 194								4 194
1905-1909	898								898
1910-1914	73 215								73 215
1915-1919	2 205								2 205
1920-1924	21 551								21 551
1925-1929	79 386				75				79 461
1930-1934	41 738				91				41 829
1935-1939	24 031								24 031
1940-1944	11 204							80	11 284
1945-1949	10 669				615				11 284
1950-1954	30 127				560			515	31 202
1955-1959	21 980				3 170		6 935		32 085
1960-1964	45 876		23		4 986		2 605		53 490
1965-1969	55 823				6 701		450		62 974
1970-1974	110 363		325		14 351		1 153		126 192
1975-1979	102 388		1 999		69 760		239	620	175 006
1980-1984	84 418		4 156	3 163	11 251				102 988
1985-1989	51 284		296		12 925				64 505
1990-1994	31 128	10 715	9 178	570	7 258	1 939			60 788
1995-1999	2 170	78 181	12 424	536	124	6 883			100 318
>2000		55 744	9 765	2 319	21	14 367			82 215
TOTAL	**809 029**	**144 641**	**38 166**	**6 587**	**131 888**	**23 188**	**11 382**	**1 215**	**1 166 097**

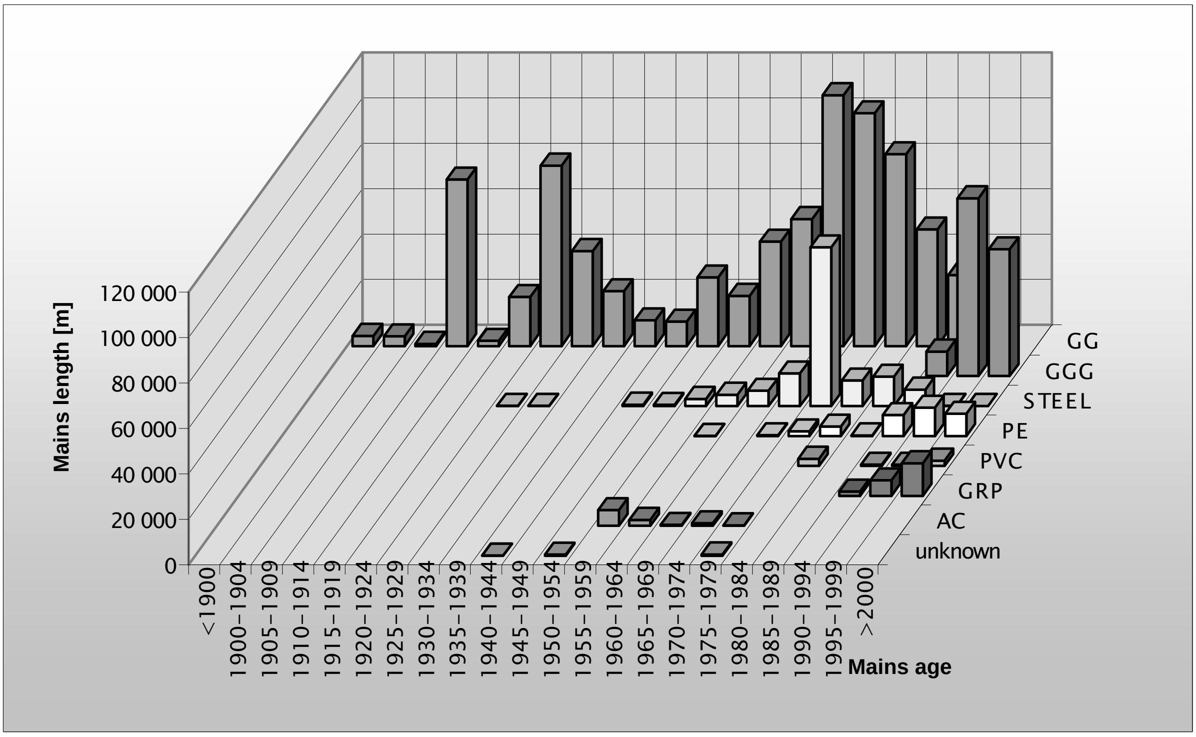

Fig. 1: *Water mains material and age*

Every year BVK, a.s. takes over some constructions of new water mains funded by private investors. The greatest construction in 2001 was the southern part of the Vír regional water supply system. It consists of 27,6 km of water mains (DN 300, 250, 150, 125, 100) using ductile iron and polyethylene pipes. Water supply system connects the Rajhrad water reservoir to reservoirs in Sokolnice and Tešany and enables supply of many other villages. Tab.2 and fig.2 shows the overview of water mains constructions.

Tab. 2: *Water mains constructions*

MAINS LENGTH [m]			updated: December 31, 2001
Year	**New**	**Rehabilitated**	**Re-laid**
1994	8 975	8 307	748
1995	6 568	7 425	3 482
1996	6 262	12 751	3 672
1997	11 254	12 087	1 829
1998	5 631	10 217	3 809
1999	21 045	14 362	775
2000	15 349	15 908	367
2001	33 777	12 535	1 920

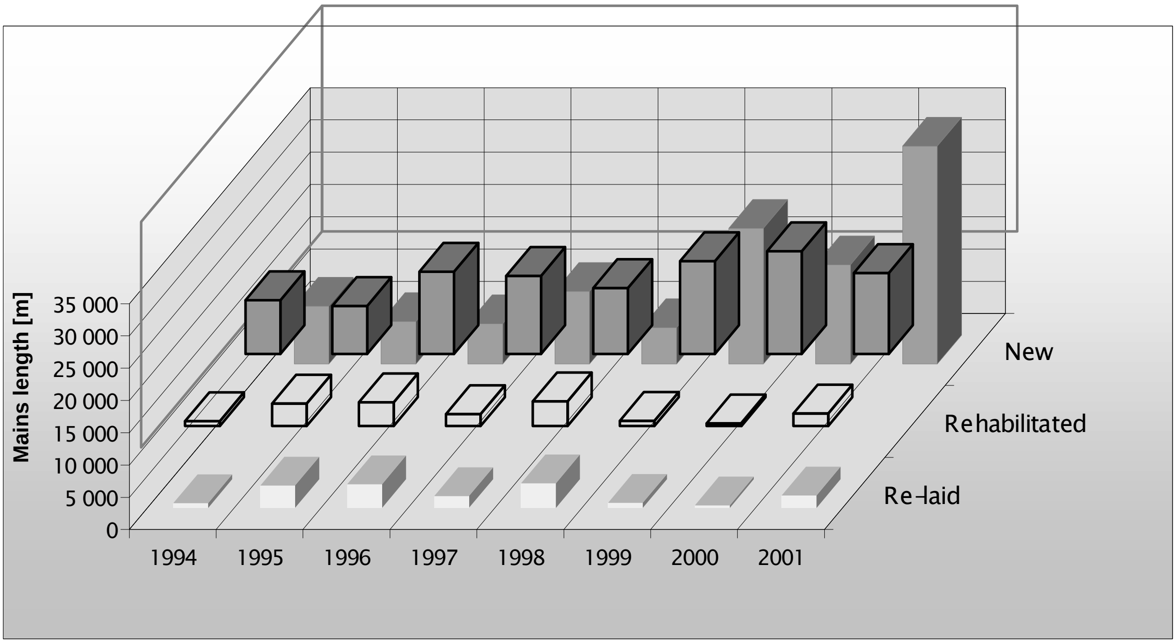

Fig. 2: *Water mains constructions*

The following table (tab. 3) shows rehab technologies applied since 1994 on the Brno water distribution network. There are three groups of rehab technologies:

R1 – Rehabilitation in the open cut without a change of DN or line
R2 – Rehabilitation in the open cut with a change of DN or line
R3 – Rehabilitation using trenchless technologies

Tab. 3: *Water mains rehabilitation*

MAINS LENGTH [m]						updated: December 31, 2001
YEAR	REHAB TECHNOLOGY			Total rehabilitated mains length	Total mains length	Mains rehabilitation
	R1	R2	R3			
1994	2 607	5 110	590	8 307	1 022 796	0,81%
1995	3 770	744	2 911	7 425	1 029 103	0,72%
1996	4 203	1 334	7 214	12 751	1 076 510	1,18%
1997	5 956	1 891	4 240	12 087	1 086 694	1,11%
1998	4 621	2 289	3 307	10 217	1 086 206	0,94%
1999	4 612	5 090	4 660	14 362	1 105 422	1,30%
2000	3 018	5 704	7 186	15 908	1 133 424	1,40%
2001	1 279	8 189	3 068	12 535	1 166 097	1,07%
TOTAL	30 065	30 350	33 177	93 592		

33,18km of water mains were rehabilitated using trenchless technologies since 1994. Most of them were rehabilitated with cement mortar (52%) and epoxy lining (39,5 %). See tab. 4.

Tab. 4: *Water mains rehabilitation using trenchless technologies*

MAINS LENGTH [m]				updated: December 31, 2001
YEAR	TRENCHLESS TECHNOLOGY			Total rehabilitated mains length
	Cement mortar	Epoxy lining	Fabric coat	
1994	590			590
1995	2 387		524	2 911
1996	7 214			7 214
1997	1 880	1 690	670	4 240
1998		3 240	67	3 307
1999	1 863	2 797		4 660
2000	2 898	2 840	1 448	7 186
2001	413	2 530	125	3 068
TOTAL	17 245	13 098	2 834	33 177
%	52,0%	39,5%	8,5%	

2. FAILURES ANALYSIS

In this study we are using the term **(*water) mains failures***. It is necessary to explain that this indicator differs from the one defined in WP1 report – Op26 Mains failures. Unlike the PI Op26, our indicator "*mains failures*" includes only *pipe failures (Op26a)* and *joint failures (Op26b)* and it does not include *valves failures (Op26c).* As our end-user registers only number of valve failures that are not assigned to water mains, we suggest using the PI Op26 Mains failures as a sum of pipe and joint failures only.

Tab. 5 shows a general view of mains failures on the whole water distribution network in the city of Brno since 1990. The last column *Mains rehabilitation* is taken from the tab. 3.

Tab. 5: *Water mains failures*

updated: December 31, 2001				
Year	**Mains failures**	**Mains length**	**Mains failures**	**Mains rehabilitation**
	No.	**km**	**No./100 km/year**	**% / year**
1990	304	1 005	30,25	N/A
1991	357	1 014	35,21	N/A
1992	267	1 001	26,67	N/A
1993	314	1 014	30,97	N/A
1994	337	1 023	32,94	0,81%
1995	284	1 029	27,60	0,72%
1996	385	1 077	35,75	1,18%
1997	353	1 087	32,47	1,11%
1998	348	1 086	32,04	0,94%
1999	322	1 105	29,14	1,30%
2000	318	1 133	28,07	1,40%
2001	307	1 166	26,33	1,07%

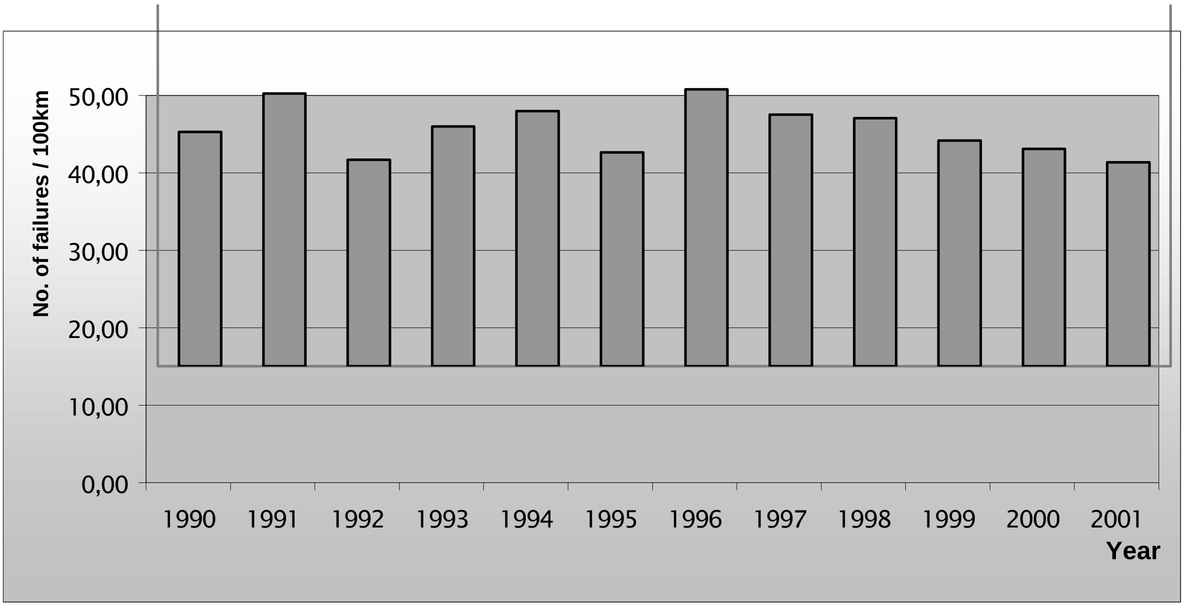

Fig. 3: *Water mains failures*

In 2001 3576 failures were notified, which is 99 failures more than in 2000. Most failures causing water leakage and water supply limitation were repaired within 24 hours after their detection. Failures not causing water leakage were repaired continuously.

Tab. 6: *Reported and repaired failures in 2001*

Number of failures			updated: December 31, 2001
	Type of failure	**Reported failures**	**Repaired failures**
WM	Water mains failures	307	278
V	Valves failures	700	580
H	Hydrant failures	703	655
S	Service connection failures	679	673
SF	Service connection fitting failures	1 022	912
O	Other failures	165	158
	Total	**3 576**	**3 256**

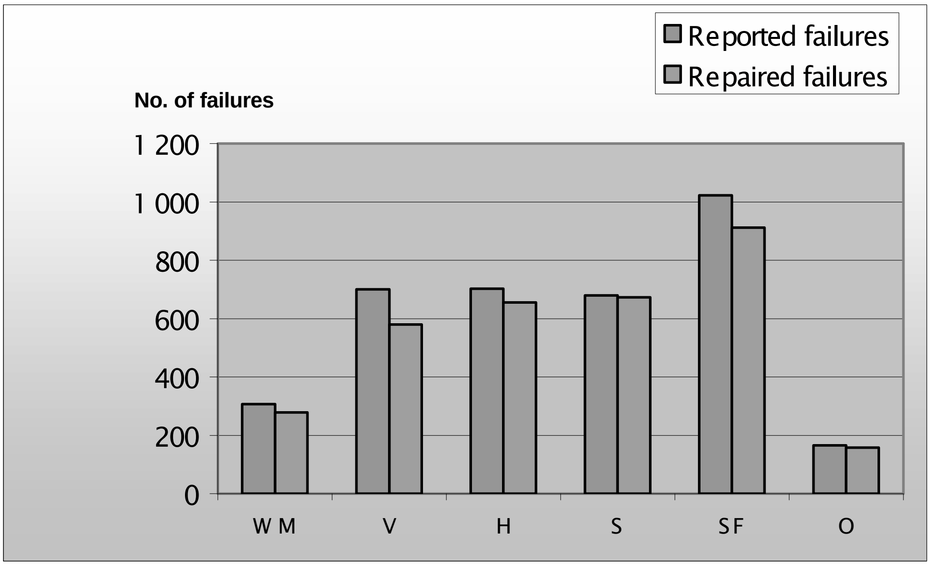

Fig. 4: *Reported and repaired failures in 2001*

SINTEF The Foundation of Scientific and Industrial Research, Trondheim, Norway
Norwegian University of Science and Technology, Trondheim, Norway
Brno University of Technology, Brno, Czech Republic
Cemagref, Bordeaux, France
Dresden University of Technology, Dresden, Germany
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