A RESEARCH PROJECT SUPPORTED BY THE EUROPEAN COMMISSION UNDER THE FIFTH FRAMEWORK PROGRAMME
AND CONTRIBUTING TO THE IMPLEMENTATION OF THE KEY ACTION "SUSTAINABLE MANAGEMENT AND QUALITY OF WATER"
WITHIN THE ENERGY, ENVIRONMENT AND SUSTAINABLE DEVELOPMENT

EVK1-CT-2000-00053

REPORT

No. 2.2 - October 2003

WP2
Description and Validation of Technical Tools

D4 – Report on Tests and Validation of Technical Tools

Patrick Eisenbeis[1], Katia Laffréchine[2] Pascal Le Gauffre[2], Yves Le Gat[1], Jon Røstum[3], Ladislav Tuhovcak[4], Pavel Valkovic[4]

[1]Cemagref Bordeaux, [2]INSA Lyon, [3]NTNU, [4]Brno University of Technology

COMPUTER AIDED REHABILITATION OF WATER NETWORKS

RESEARCH AND TECHNOLOGICAL DEVELOPMENT PROJECT OF EUROPEAN COMMUNITY

COMPUTER AIDED REHABILITATION OF WATER NETWORKS
RESEARCH AND TECHNOLOGICAL DEVELOPMENT PROJECT OF EUROPEAN COMMUNITY
Hydraulics and Civil Engineering Unit, Cemagref Bordeaux, 50, avenue de Verdun, F-33612 CESTAS Cedex
Phone: +33-557.89.08.00 Fax: +33-557.89.08.01 Email: carew@bordeaux.cemagref.fr

CARE – W

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

WP2: Description and validation of Technical tools

WP2.2: Tests and validation of Technical Tools[1]

Deliverable D4

Authors: Patrick Eisenbeis (Cemagref), Katia Laffréchine, Pascal Le Gauffre (INSA Lyon), Yves Le Gat (Cemagref), Jon Røstum (NTNU), Ladislav Tuhovcak, Pavel Valkovic (Brno University)

October 2003

[1] *Reference*:
EISENBEIS P., LAFFRÉCHINE K., LE GAUFFRE P., LE GAT Y., ROSTUM J., TUHOVCAK L., VALKOVIC P. (2003) *CARE-W: WP2 – Description and validation of Technical tools D4 – Report on the tests and validation of technical tools.* CARE-W (Computer Aided Rehabilitation of Water networks), EU project under the 5th Framework Program, contract n°EVK1-CT-2000-00053. Cestas (F): Cemagref, October 2003, 54 p. + appendices (electronic document)

Table of contents

1. INTRODUCTION

1.1. CARE-W GENERAL OBJECTIVES

CARE-W project aims at developing methods and software that will enable engineers of the water undertakings to establish and maintain an effective management of their water supply networks, rehabilitating the right pipelines 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 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.

1.2. WORK PACKAGE 2 OBJECTIVES

Cemagref is responsible for WP2, which is divided in three Tasks. This report refers to the Task 2.2. "Test and validation of technical tools".

This task has several objectives:

- to test and compare the models on several water networks, that have different characteristics (size, geographical specificities, hydraulic conditions, material, type of data, maintenance data, …),
- to have a critical look on the models, with the aim of validating and fitting them,
- to improve and make their utilisation easier,
- to help to define a best use procedure.

2. CRITERIA USEFUL FOR THE ELABORATION OF AN ANNUAL REHABILITATION PROGRAM (ARP)

Decision process concerning Annual Rehabilitation Program will be based on Multi-Criteria Techniques. Report D6 (Le Gauffre et al., 2002) presents the criteria chosen for the ARP. Two types of points of view are defined :

1. "Internal" points of view (points of view of the operator) corresponding to technical concerns and technical costs such as:

- Rehabilitation costs,
- Repair costs,
- Water losses and corresponding costs,
- Energy cost.

2. "External" points of view (of customers, road users, etc.):

- disruptions associated with a particular rehabilitation method,
- impacts of water interruptions,
- damages and disruptions caused by bursts or repairs,
- water quality deficiencies,
- hydraulic deficiencies.

Criteria and sub-criteria have to be defined to evaluate and compare candidates according to these various points of view.

This led to the definition of criteria proposed in Table 2. For the assessment of the criteria, some information has to be known. This information is classified in Performance Indicators (PI), Utility Information (UI) or External Information (EI).

Each criterion can be assessed by two mains ways:
- using formula including PI, UI or EI ; for instance Annual Repair Costs Formula is:

$$ARC\ (i,j) = PFR(i,j)\ .\ UCR(i)$$

with UCR(i) Unit Cost of Repair and PFR(i,j) Predicted Failure Rate ;

- using "Mark " Table ; for instance Reduction of Discoloured Water Problems (*RDW*) will depend on two sub-criteria : the level of problem regarding Discoloured Water in the corresponding Zone (*DWZ*) and the reduction of the contribution of pipe to discoloured water in the corresponding Zone (*RCDW*).

$DWZ(i)$ and $RCDW(i,j)$ can be combined according to an evaluation table as in Table 1:

Table 1 : Example of "Mark" Table for criteria evaluation

L3	0	3	6	10
L2	0	2	4	6
L1	0	1	2	3
L0	0	0	0	0
	No reduction	C3→C2 C2→C1 C1→C0	C3→C1 C2→C0	C3→C0

In this table the L0, L1, L2 and L3 correspond to different levels of water colour problems in the zone and C0, C1, C2 and C3 the different contribution of the pipe to discoloured water problems in the zone.

In the second case, no formula can be proposed because of the difficulty to calculate the effect of a pipe on a zonal discoloured water problem.

Among all the sub-criteria useful for calculation of rehabilitation criteria, some of them can now be computed and assessed with the aid of scientific tools : these are <u>Predicted Failure Rate</u>, that can be computed with statistical tools based on failure historic, and <u>Pipe Hydraulic reliability</u>, that can be assessed using mathematical hydraulic models crossed with failure risks.

Table 2 : Points of view, criteria, and required information for Annual Rehabilitation Program

Point of view	Criteria	Information
Rehabilitation costs	AUCR	Annual Unit Cost of Rehab. *CSF Co-ordination cost saving factor*
Co-ordination	COS	Co-ordination score • Schedule of service connection rehab • Schedule of road work • Schedule of other utility rehab
Repair costs	ARC	Annual Repair Costs • Cost table, mean costs • Street category • Failure rate
Water losses and relative costs	WLI	Water losses index • Failure rate observed • Leakage cost • Failure rate
Disturbances induced by rehab measure	DRM DS	Disturbance index • technique scoring table • Service connection density • Street category • Sensitive customer • Coordination with road work • Coordination with other utility
Water interruptions	PWI PCWI PFWI	Predicted Water Interruption Pr. Critical Water Interruption • Predicted Burst rate • Duration of interruption • No of people supplied by the link • (No of) Sensitive Customers supplied by the link Pr. Frequency of WI
Damages and disruptions	DFH DFI DSM DT DDI	Damage due to Flooding in Housing areas, or Industrial or Commercial areas. Damage due to soil movement Traffic Disruptions Damage and/or Disruption on other Infrastructure • Diameter • Pressure • Slope • Risk of landslide • Street category • Basement • Ground Floor above soil • Type of housing • Type of activities • Sensitive infrastructure close to the link • Failure rate • Burst rate
Water quality Deficiencies	WQD	Water quality deficiencies • Quality of water • Customer complaints • Material • Installation date
Hydraulic reliability	HCI	Hydraulic criticality index • Mean duration of repair • Failure rate

These tools, accurately presented in the D3 report of CARE-W (Eisenbeis et al, 2002), are the object of the task 2 of WP2. This task aimed to test and validate the models in some European water networks.

3. PRESENTATION OF THE MODELS

All the models are presented in a detailed way in the D3 Report (Eisenbeis et al, 2002). The paragraphs below give a synthesis of objectives, methods, input and output of each model.

3.1. FAILURE FORECAST MODELS OR ANALYSIS (CARE-W FAIL TOOLS)

These models aim to provide methods to assess Failure risks. Their objectives are multiple:

- defining influences of pipe related and environmental variables: significance of the variables is tested and their weight is computed,
- defining failure risk functions: based on previous outputs and on chosen model (Weibull, Poisson), Failure risk functions are built pipe by pipe, category by category,
- forecasting number of failures or failure rates: this forecast is set up either directly (NHPP) or using failure risk functions,
- defining survival functions: by knowing the failure risk functions, pipe category survival functions are built.

Table 3 presents the models and their objectives.

Table 3: Main outputs of the Failure Forecast Models

	Variables influence	Failure risk functions	Failure Forecast	Survival functions
Care-W_Poisson *(INSA Lyon)*	X	X	X	
Care-W_PHM *(Cemagref)*	X	X	X	
NHPP Model [2] *(NTNU)*	X		X	
Markov Model[3] *(INSA Lyon)*				X

3.1.1. Care-W_Poisson (INSA-Lyon)

Figure 1 presents the different steps of Care-W_Poisson. Outputs of Care-W_Poisson are:

- **The influence of failure factors, which can be characterised with Rate Ratios calculated by the Poisson Regression.**

For instance, RR(Under Roadway / Under Footpath) = 2.0 means that the failure rate for sections situated under roadway is estimated to be 2 times higher than the failure rate for sections situated under footpath.

[2] NHPP Model has been tested only on one Network (Trondheim). It will not be included in the 1st version of CARE-W .

[3] Markov Model elaboration is still in progress. It will mainly be useful for Long Term Rehabilitation Strategy.

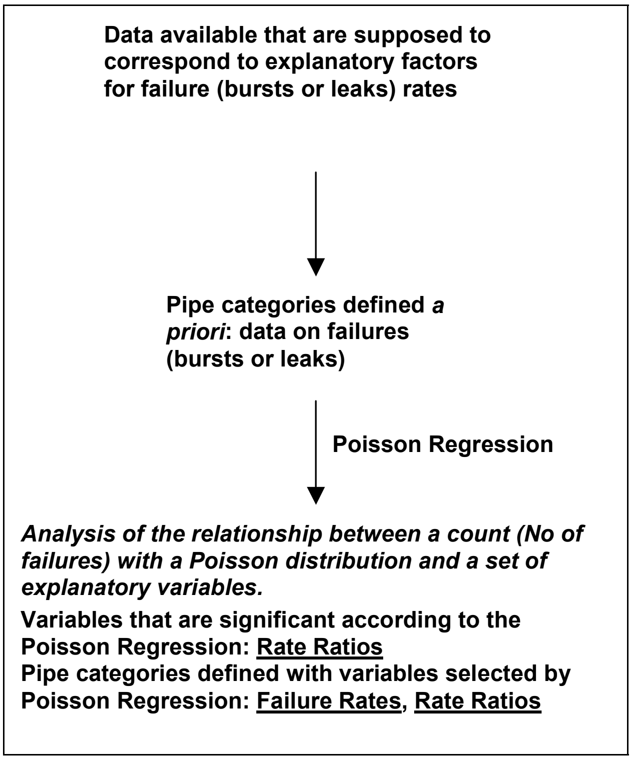

Figure 1 : Description of Care-W_Poisson steps

Statistical tests and confidence intervals for Rate Ratios allow selecting a set of significant variables.

- **Classification of the asset in several pipe categories, defined in combining the statistical variables that are significant according to the Poisson Regression Analysis**

- **Computation of the Failure Rate for category (FR).**

This predicted failure rate can be applied to a single section in addition to information available for this section.

- Computation of Rate Ratio by category: $RR(C_i) = FR(C_i)/Reference\_Failure\_Rate$

Finally a set of indices can be calculated in order to evaluate the efficiency of the dividing of the asset into categories: e.g. *%TL(80)=% of the total length corresponding to 80% of the failures.*
This enables to test different renewal hypotheses on these categories.

- Attribution of Failure Rate to each Pipe

The value finally attributed to each pipe is the maximum between two values :
- Failure rate value of the category which pipe belongs to,
- Individual pipe failure rate.

3.1.2. Proportional Hazard Model (PHM) (Cemagref)

The main objective of PHM model (Figure 2) is to portray approximately the distribution of the random variable consisting in the number of predicted failures. A given section of drinking water network is likely to be subjected to in a given time horizon.

The main output of the model is the predicted failure rate (PFR, number of future failures per km per year) of each section of the network. This value can finally be also aggregated at the level of a category of pipes (e.g. of same material and diameter), or a sub network, or the whole network.

PHM model is based on the statistical survival analysis of the past failures dates (maintenance data over at least 5 years) observed for each section of the network (pipeline homogeneous in material, diameter, road location and installation date). These occurrences are probabilistically explained by a set of covariates either proper to the sections of the network or related to their environmental conditions, influencing proportionally the failure risk.

The key analysis variable is the inter failure time, which distribution is modelled by a Weibull distribution function which depends on a scale parameter and a position parameter designed as a linear combination of the covariates. The analysis is stratified by material and number of observed previous failures. The parameter estimates are computed via the maximization of the log likelihood function of the observed inter failure times, including those right censored by the observation stopping date or the removal date of the sections.

The number of future failures for each section is estimated by Monte Carlo simulations.

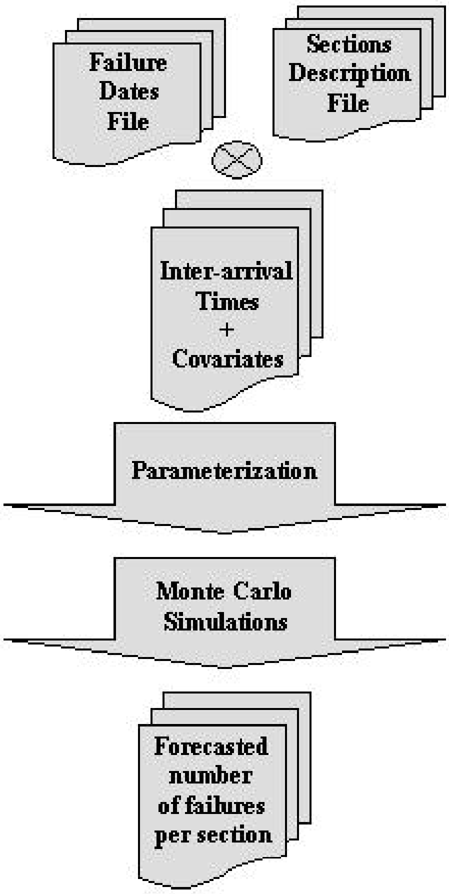

Figure 2: Description of Care-W_PHM steps

3.1.3. Non Homogeneous Poisson Process (NHPP) (SINTEF-NTNU)

The main objective of WINROC is to predict failures for each individual pipe in a water distribution network based on historical failure data. The relative importance of different explanatory variables is reported by its regression coefficients.
WINROC models the failure-process in water supply networks as a Non Homogeneous Poisson Process (NHPP) which also takes into account the factors influencing (e.g. material, diameter, length) the failure history. The relative importance of the explanatory variables is reported and future failures for each pipe in the network are predicted. (Figure 3)

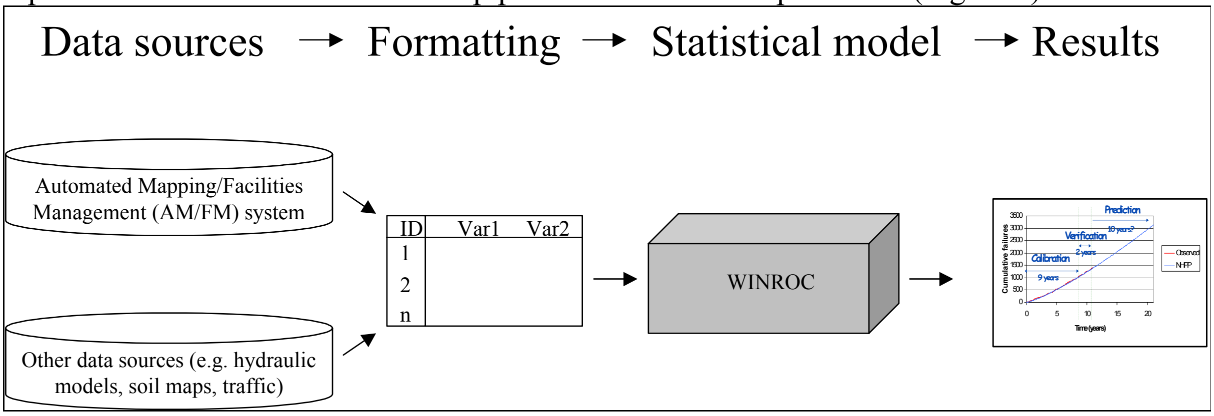

Figure 3: Description of NHPP steps

3.1.4. Markov model (INSA)

The Markov model presented in report D3 (Eisenbeis *et al*., 2002) has been modified for a better connection with the tool developed for the long-term strategic planning (new version of KANEW – work package 4).

The aim of the Mv3 model is the following:

- using break history and rehabilitation history,
- provide a support to the calculation of survival functions used in KANEW,
- for each pipe category defined according to ageing factors and performance requirements (associated with a particular urban environment).

Markov model is designed to be used in a procedure that is presented in the Figure 4.

① Pipe categories have to be defined in taking account of ageing factors (that can be known or identified with the statistical analysis provided in CARE-W) and performance requirements.

② For each category, the Markov model is designed to use the failure history and the rehabilitation history for the calibration of ageing functions. These ageing functions could be used to support the definition of lifetimes and survival functions used in the LTS module (KANEW).

This model, still in progress, has not been tested in the project CARE-W.

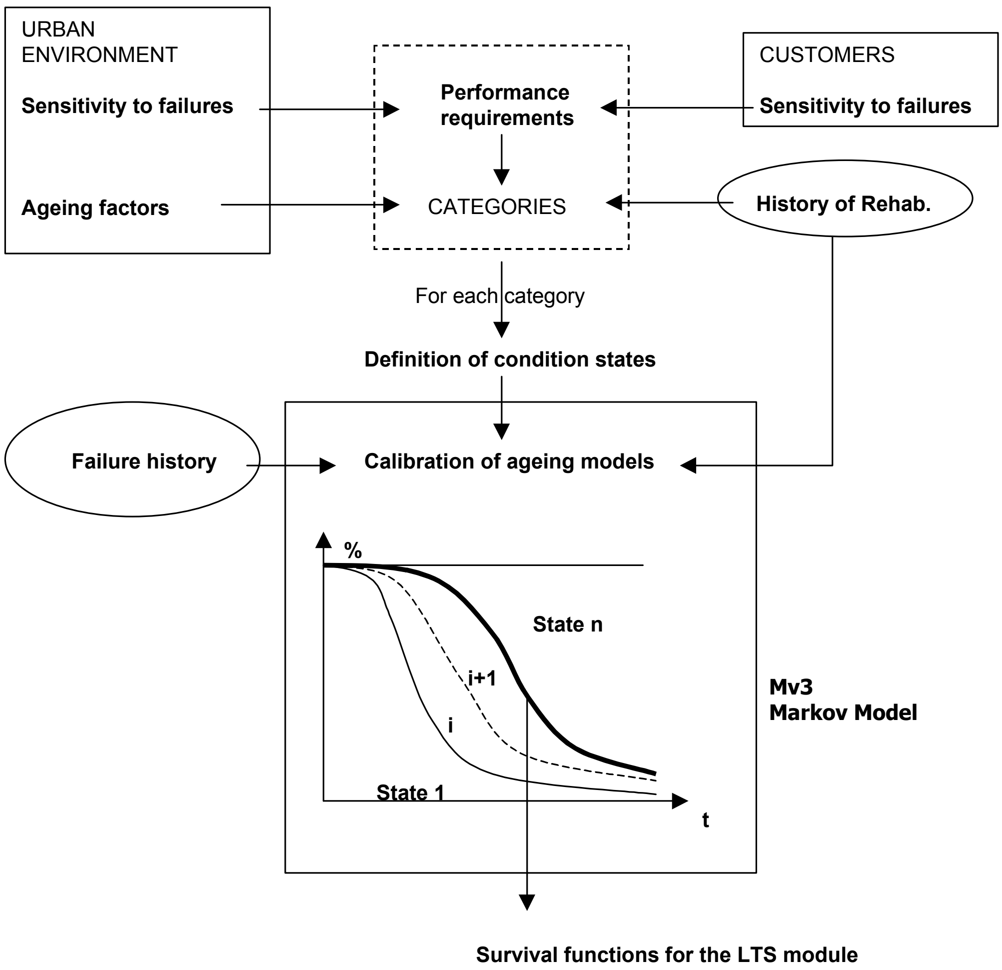

Figure 4 : Markov model procedure

3.2. HYDRAULIC RELIABILITY MODELS (HRM)

These tools consist in models and methods to assess several indicators linked with hydraulic availability:

- defining pipe failure impact on demand or pressure and consequently defining pipe hydraulic importance,
- defining global network hydraulic reliability,
- defining Hydraulic Critically Index (HCI) useful for ARP.

The difference between the proposed models concern principally hydraulic modelling and the way to assess and measure the different reliability indices.

3.2.1. Failnet-Reliab (Cemagref)

This tool aims at assessing the **reliability of drinking water networks**. Reliability is defined in the sense of water demand satisfaction, and, basically, it is the quotient between the available consumption and the water demand.
After a specific hydraulic modelling, where available consumption is computed according to the head at each node, several reliability indices are assessed and can be used as performance indicators (PI). The different scales of assessment are:
- **pipes**: this is the impact of a pipe break on all the nodes of the network,

- **nodes**: this is the reliability of supply at the node in relation with all the links,
- **global network** (or a sector): this is overall reliability of the network.

The model is elaborated in two steps (Figure 5):
- First an hydraulic model is computed. This model differs from classical hydraulic models, because water consumptions are not fixed and depend on computed heads and water demands. Newton-Raphson method is used to solve hydraulic equation and compute the outputs.
- Secondly reliability indices are assessed. They depend on the results of hydraulic models (with or without pipe breaks), on weight of each nodes (quantity, vulnerability) and on pipe failure probabilities (assessed or not with forecast probability models). They represent the volume of non-supplied water in the year because of failure risk.

Necessary data are classical hydraulic data (**node**: altitude, water demand, kind of water use, **pipe**: roughness, length, diameter, **tank**: volume, altitude, **pumps**…) and, optionally, failures probability.

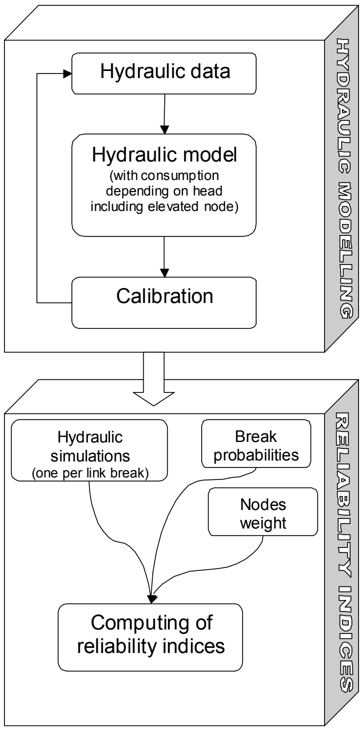

Figure 5 : Description of Failnet-Reliab steps

3.2.2. Aquarel (SINTEF-NTNU)

AQUAREL calculates reliability measures for water distribution networks allowing simultaneous failures of equipments. (Figure 6)
The approach is based on hydrostatic simulations of the conditions in the network (EPANET 2.0) combined with standard reliability calculation techniques. The idea is to close the links in the network and examine the effect on the supply nodes using EPANET. The model also takes into account the volume-effect of the elevated reservoirs (tanks).
As input data AQUAREL requires the failure and repair rate for all links (i.e. pipes and pumps) in the network. AQUAREL calculates several reliability measures at pipe (i.e. node)

level (i.e. water supply availability, frequency of degraded pressure, link importance_ B, link importance_ U and link importance_ F).

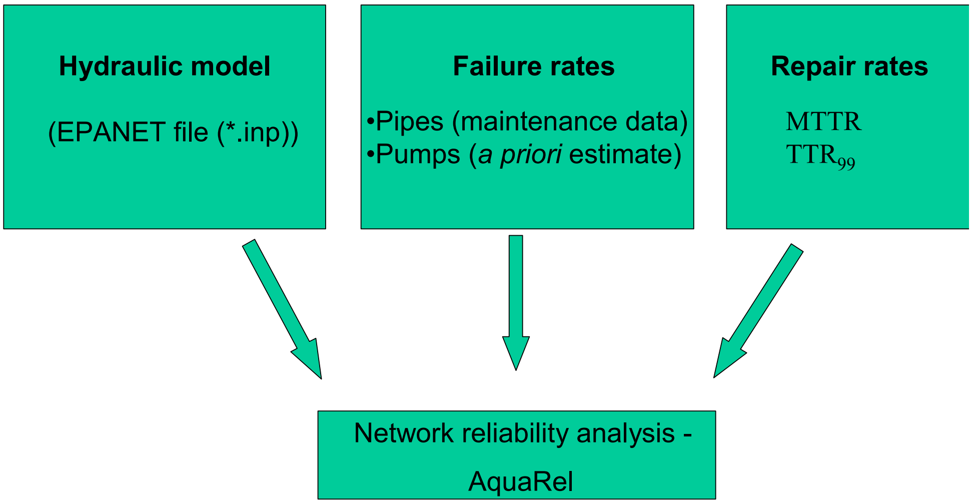

Figure 6: Description of Aquarel steps

The system reliability is dependent on the hydraulics in the network, the failure rate and the repair rate. Failure rates and repair rates vary from link to link. The integration and following evaluation of these elements leads to a water network reliability analysis.

3.2.3. RelNet (BUT)

The aim of this model is to assess hydraulic reliability of each node, the total hydraulic reliability of the network and hydraulic critical index (HCI) of each pipe section. Reliability of the water distribution network depends on reliability of network elements (nodes and pipe sections). Reliability is based on required pressure in each node and undelivered water in whole network. (Figure 7)

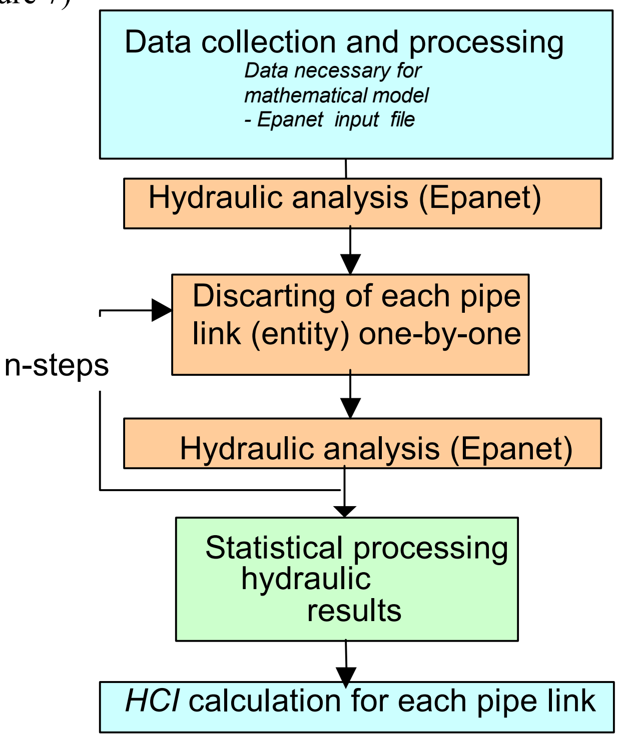

Figure 7: Description of Relnet steps

HCI processing - algorithm description:

1. Calculation of actual head pressure and demand in the each node in the network, in the original state of the network diagram. None of the pipe links is discarded. Results are Q_{act} (actual demand), H_{act} (actual pressure) and sum of Q (Q_{total}).
2. One pipe link is discarded from the total *n* pipe links in the network. The network pressure analysis and calculation of pressure in each node (H_{new}) and calculation of demand (Q) is realized.
3. Description of HCI calculation :

   HCI of the discarded link is calculated from the volume of undelivered water in the entire network. The amount of undelivered water in each node depends on the calculated pressure value (H_{new}).

   if $H_{new} < H_{min}$ then $Q_{new} = 0$

   If the H_{new} value is lower than H_{min} the consumer demand is not satisfied and the amount of delivered water is 0 in this node.

   if $15 < H_{new} < H_{req}$ (25 m recommended)

   then the amount of delivered water in the node is reduced and is calculated according to the following formula

   $$Q_{new} = Q_{act} * \frac{\sqrt{H_{new}}}{\sqrt{H_{act}}}$$

   If $H_{new} > H_{req}$ (25 m recommended) then the consumer demand is fully satisfied and delivered water $Q_{new} = Q_{act}$ (nothing has changed).

   Delivered water Q_{new} is calculated by this method for each node of the network.
4. HCI calculation: The total sum of Q_{new} is calculated over all nodes of the entire network. Then the HCI is calculated according to the following formula

   $$HCI = \frac{Q_{total} - \sum Q_{new}}{Q_{total}}$$

   A higher value of HCI means a higher impact of the discarded link on the total network reliability. If the sum of $Q_{new} = 0$ then no demand is satisfied in all nodes of the network and HCI = 1.

   If sum of $Q_{new} = Q_{total}$, HCI = 0 then demand is fully satisfied at the required pressure.

4. TESTS METHODOLOGY

This task has several objectives:

- to test and compare the models on several water networks, that have different characteristics (size, geographical specificities, hydraulic conditions, material, type of data, maintenance data, …),
- to have a critical look on the models, with the aim of validating and fitting them,
- to improve their use and make it easier,
- to help to define a best use procedure.

4.1. FAIL TOOLS

4.1.1. Objectives of the tests for FAIL tools

The objectives are to test whether the models fit the reality. This has been done either on whole networks or on categories of pipes (principally by material).

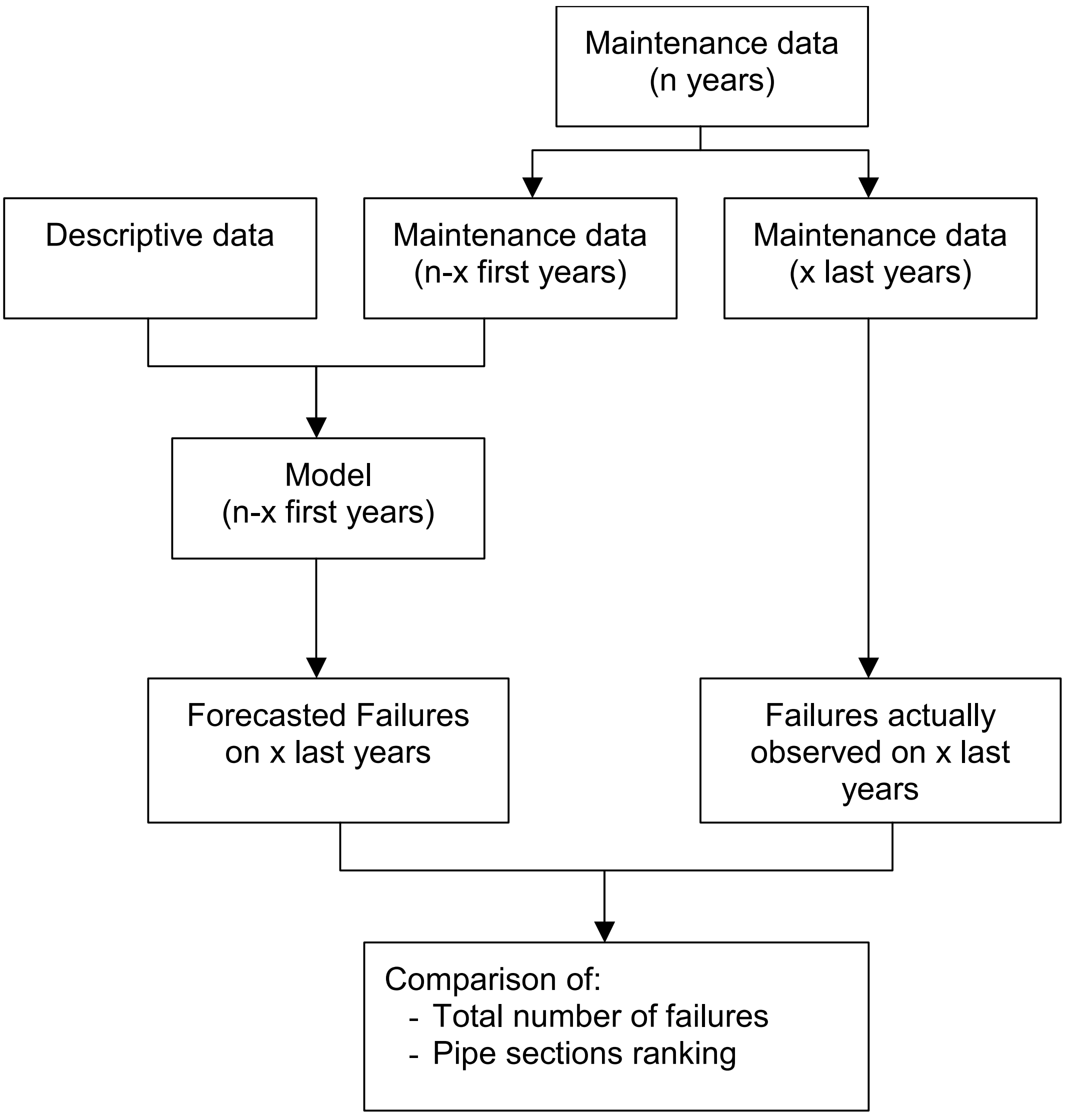

Figure 8: Comparison of forecasted vs. actually observed failures

For each network, where historic maintenance data have been recorded for *n* years, the model was parameterised with the sole first *n-x* years and the results were compared to the *x* last years. (Cf. Figure 8)

For each model several tests were done with various combinations of :
- the length of the historic (n),
- the length of the time horizon (x).

For "Benefit" index (Cf. 4.1.4), one checked whether the results were better on the very first links (1% for instance, that is close to classical rehabilitation rate) or on a larger set (10, 25 or 50%).

A difficulty of this test is caused by the disappearance of the data related to replaced segments. This could make artificially depart the models from the reality.

The tests aimed to compare the results of different models (Figure 9). Different indices were used. This comparison was done on :
- total numbers of failures,
- rankings,
- influencing factors.

It was also done either on whole networks or pipes categories.

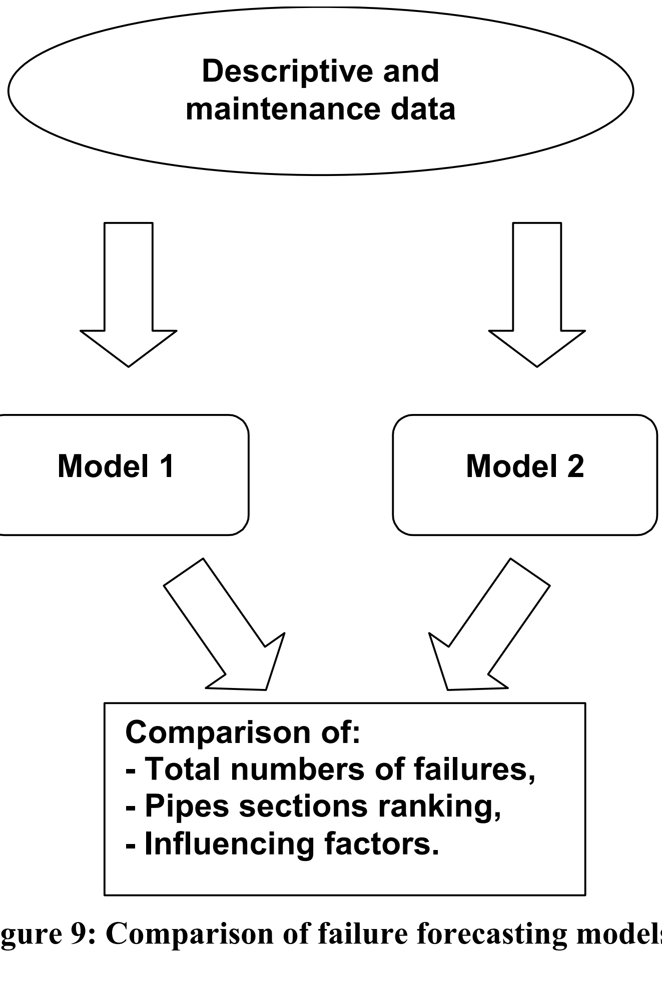

Figure 9: Comparison of failure forecasting models

4.1.2. Estimated indices

Several different validations were performed.

For forecasting models, the validation consisted in:

- comparing the forecast results (with complete or uncompleted data) with the reality ; Two indices were proposed: one that gives a "Mark" to the model and one, more practical, that gives the benefit of the choice of the pipes to be replaced in term of reduction of the number of failures;
- comparing the results of 2 different models (or complete model to model with uncompleted or uncertain data) ; the comparisons of the two previous indices are used.

For each comparison model-reality and model-model, the indices values were calculated and these values were tested against the null hypothesis according to which the results are purely random.

Indices computations were carried out under SAS system.

4.1.3. "Mark" index

4.1.3.1. Definition

One interesting problem, which has been addressed neither in the statistical literature nor in the practical Cemagref studies, consists in building a tool to measure the usefulness of a given covariate, from the point of view of the forecasting ability of the model.

It is here proposed to build first an index to characterize the efficiency of the model to forecast the failure risk. In the sequel, this index is called the Failure Risk Forecasting Efficiency (FRFE) and denoted Φ, and can be computed in the model validation phase previously described. The model validation phase can then be performed twice:

a first time with the complete model, *i.e.* using all covariates found as being significant in the calibration phase, including the covariate which contribution to the forecasting ability of the model is to be assessed,

and a second time with the reduced model, *i.e.* deprived of the given covariate.

If the FRFE obtained with the complete and the reduced model are respectively denoted Φ_+ and Φ_-, the difference $\Phi_+ - \Phi_-$ measures the contribution of the given covariate to the forecasting ability of the model.

It is proposed to compute the FRFE as follows. Let first the random variable N_i stand for the number of failures the i^{th} section may be subjected to in the time interval $[t_v, t_{ib}]$. The number of failures actually observed in this interval is denoted by $\tilde{N}_i$, and the expected value (*i.e.* forecasted by the model) by $\hat{N}_i$. The c sections are then ranked in three ways:

the first ranking consists in sorting out the sections by descending values of expected numbers of failures $\hat{N}_i$ and the resulting ranks are denoted by $\hat{R}_i$; this means that:

$$\hat{N}_k = \underset{i=1\ldots c}{Max}\left(\hat{N}_i\right) \Rightarrow \hat{R}_k = c \text{ and } \hat{N}_k = \underset{i=1\ldots c}{Min}\left(\hat{N}_i\right) \Rightarrow \hat{R}_k = 1 \ ;$$

the second ranking consists in sorting out the sections by descending values of observed numbers of failures $\tilde{N}_i$ and the resulting ranks are denoted by $\tilde{R}_i^+$; this means that:

$$\tilde{N}_k = \underset{i=1\ldots c}{Max}\left(\tilde{N}_i\right) \Rightarrow \tilde{R}_k^+ = c \text{ and } \tilde{N}_k = \underset{i=1\ldots c}{Min}\left(\tilde{N}_i\right) \Rightarrow \tilde{R}_k^+ = 1 \ .$$

the third ranking consists in sorting out the sections by ascending values of observed numbers of failures $\widetilde{N}_i$ and the resulting ranks are denoted by $\widetilde{R}_i^-$; this means that:
$\widetilde{N}_k = \underset{i=1\ldots c}{Max}\left(\widetilde{N}_i\right) \Rightarrow \widetilde{R}_k^- = 1$ and $\widetilde{N}_k = \underset{i=1\ldots c}{Min}\left(\widetilde{N}_i\right) \Rightarrow \widetilde{R}_k^- = c$.

The quantity $\sum_{i=1}^{c} \hat{R}_i \widetilde{N}_i$ can take any integral value between $\sum_{i=1}^{c} \widetilde{R}_k^+ \widetilde{N}_i$ and $\sum_{i=1}^{c} \widetilde{R}_k^- \widetilde{N}_i$.

It is then proposed to define the FRFE as:

$$\Phi = \frac{\sum_{i=1}^{c} \hat{R}_i \widetilde{N}_i - \sum_{i=1}^{c} \widetilde{R}_k^- \widetilde{N}_i}{\sum_{i=1}^{c} \widetilde{R}_k^+ \widetilde{N}_i - \sum_{i=1}^{c} \widetilde{R}_k^- \widetilde{N}_i} \tag{7}$$

The FRFE index Φ has the property: $\Phi \in [0,1]$. If the model produced a perfect forecast, the ranks $\hat{R}_i$ and $\widetilde{R}_i^+$ should be equal for all sections, and thus $\Phi = 1$, which means that the perfect model has a forecasting efficiency of 100 %. It is important to notice that FRFE does not measure the exactness of the forecasted numbers of failures, but rather the ability to correctly rank the sections according to their actual risk of failure.

It remains to carry out the theoretical investigation of the distribution of the FRFE considered as a random variable Φ_0 under the null hypothesis H_0 of independence between $\hat{R}_i$ and $\widetilde{R}_i^+$. This would then make it possible to compute the risk $P\left\{\Phi_0 > \Phi \mid H_0\right\}$ to reject wrongly the null hypothesis when asserting the forecasting efficiency of the model.

4.1.3.2. Example

Let a set of 10 links, of which forecasted failure probabilities have been calculated and actual failures are known, as in the Table 4.

Table 4: Example on 10 links

Link ID	Forecasted failure probability	Real failures
L1	0.21	0
L2	0.06	0
L3	0.40	2
L4	0.03	0
L5	0.09	0
L6	0.15	1
L7	0.02	1
L8	0.07	0
L9	0.26	3
L10	0.01	0

If we rank the links according to the forecasted failure probability, we have the Table 5 with $\hat{R}_i$ and $\tilde{N}_i$ and $\hat{R}_i * \tilde{N}_i$:

Table 5: Ranking links according to forecasted failure probabilities

	$\hat{R}_i$	$\tilde{N}_i$	$\hat{R}_i * \tilde{N}_i$
L3	10	2	20
L9	9	3	27
L1	8	0	0
L6	7	1	7
L5	6	0	0
L8	5	0	0
L2	4	0	0
L4	3	0	0
L7	2	1	2
L10	1	0	0

Here we have $\sum_{i=1}^{c} \hat{R}_i \tilde{N}_i = 56$, *i.e.* the efficiency mark of the forecasting process without taking into account the maximum and minimum possible values of this mark (not standardised).

To assess these values, $\tilde{R}_+$ and $\tilde{R}_-$ are given in Table 6. In case of equally placed, the average of the rank is assigned.

Table 6: Assessing $\tilde{R}_{i+}$, $\tilde{R}_{i-}$, $\tilde{R}_{i+} * \tilde{N}_i$ and $\tilde{R}_{i-} * \tilde{N}_i$

	$\tilde{N}_i$	$\tilde{R}_{i+}$	$\tilde{R}_{i-}$	$\tilde{R}_{i+} * \tilde{N}_i$	$\tilde{R}_{i-} * \tilde{N}_i$
L3	2	9	2	18	4
L9	3	10	1	30	3
L1	0	3.5	7.5	0	0
L6	1	7.5	3.5	7.5	3.5
L5	0	3.5	7.5	0	0
L8	0	3.5	7.5	0	0
L2	0	3.5	7.5	0	0
L4	0	3.5	7.5	0	0
L7	1	7.5	3.5	7.5	3.5
L10	0	3.5	7.5	0	0

Finally we have :

$\sum_{i=1}^{c} \tilde{R}_k^+ \tilde{N}_i = 63$, the maximum possible value of the Mark, if the forecast was perfect

and

$\sum_{i=1}^{c} \tilde{R}_k^- \tilde{N}_i = 14$, the minimum possible value of the Mark.

Then the index is calculated:

$$\Phi = \frac{56-14}{63-14} = 0.86$$

4.1.4. Benefit index

4.1.4.1. Definition

This index aims at assessing the number of failures avoided, if the links with the highest break probabilities were rehabilitated.

Let first the random variable N_i stand for the number of failures the *i*th section may be subjected to in the time interval $[t_v, t_{ib}]$. The number of failures actually observed in this interval is denoted by $\tilde{N}_i$, and the expected value (*i.e.* forecasted by the model) by $\hat{N}_i$. Contrarily to the previous index, the *c* sections are then ranked as follows:

- the sections are sorted out by ascendant values of expected numbers of failures $\hat{N}_i$ and the resulting ranks are denoted by $\hat{S}_i$; this means that:

$$\hat{N}_k = \underset{i=1\ldots c}{Max}\left(\hat{N}_i\right) \Rightarrow \hat{S}_k = 1 \text{ and } \hat{N}_k = \underset{i=1\ldots c}{Min}\left(\hat{N}_i\right) \Rightarrow \hat{S}_k = c \text{ ;}$$

For each pipe we can then calculate the rank percentage $\hat{p}_i$: $\hat{p}_i = \frac{\hat{S}_i}{c}$

Let $\tilde{F}_i$ be the number of failures actually observed in the i segments that have the highest failure probability:

$$\tilde{F}_i = \sum_{k/\hat{S}_k < i} \tilde{N}_k$$

And $\tilde{f}_i$ the percentage of failures actually observed in the i segments that have the highest failure probability:

$$\tilde{f}_i = \frac{\tilde{F}_i}{\sum_{i=1}^{c} \tilde{N}_i}$$

It is then possible to draw the graph (see example) of $\tilde{f}_i$ according to $\hat{p}_i$ and we propose to assess different indices $\tilde{f}_i$ according to $\hat{p}_i$ for instance 1%, 5%, 10%, 25% and 50%. The higher these values are, the better the model is.

4.1.4.2. Example

Let consider the same example as for the previous index. The Table 7 shows the ranking of the segments and the values of $\hat{S}_i$ and $\hat{p}_i$.

Table 7 : Ranking links according to forecasted failure probability

	$\hat{S}_i$	$\tilde{N}_i$	$\hat{p}_i$ (%)
L3	1	2	10
L9	2	3	20
L1	3	0	30
L6	4	1	40
L5	5	0	50
L8	6	0	60
L2	7	0	70
L4	8	0	80
L7	9	1	90
L10	10	0	100

The Table 8 gives the values of $\widetilde{F_i}$ and $\widetilde{f_i}$.

Table 8 : Results $\widetilde{F_i}$ and $\widetilde{f_i}$

	$\hat{S_i}$	$\hat{p_i}$	$\widetilde{N_i}$	$\widetilde{F_i}$	$\widetilde{f_i}$
L3	1	10	2	2	28.6%
L9	2	20	3	5	71.4%
L1	3	30	0	5	71.4%
L6	4	40	1	6	85.7%
L5	5	50	0	6	85.7%
L8	6	60	0	6	85.7%
L2	7	70	0	6	85.7%
L4	8	80	0	6	85.7%
L7	9	90	1	7	100.0%
L10	10	100	0	7	100.0%

The Figure 10 gives the graph of $\widetilde{f_i}$ against $\hat{p_i}$ for this example.

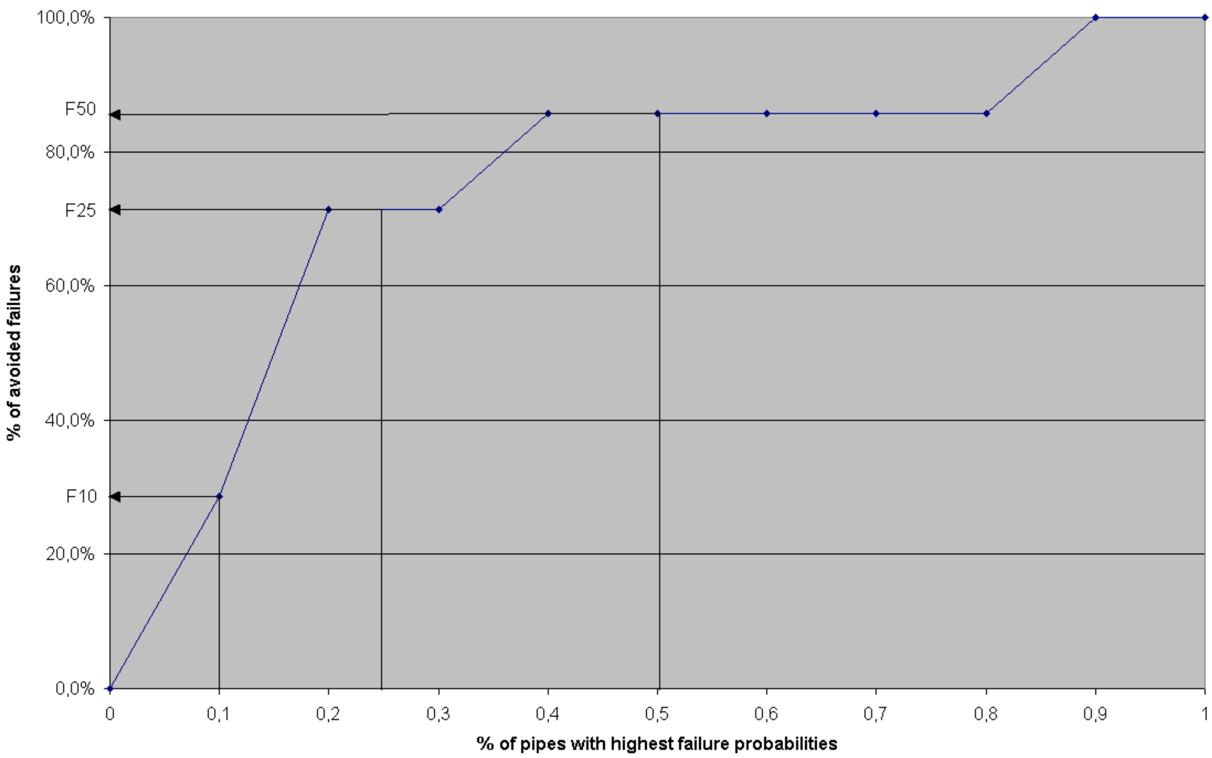

Figure 10 : Percentage of avoided failures according the percentage of first links.

Different values of $\widetilde{f_i}$ are given for 10, 25 and 50 % (1 and 5 % are not interesting here because of the small number of links).

$\widetilde{f_i}_{10} = 28.6$
$\widetilde{f_i}_{25} = 71.4$
$\widetilde{f_i}_{50} = 85.7$

4.1.5. Global synthesis for each test

Integrating the 2 models and a "simple" model (with simple ranking and assessment) and presenting the indices assessed for each test and each model.
One test depending on :

- the model,
- the failure observation time (which can be increased or decreased),
- the considered factors (environmental factors essentially).

Table 9 : Synthesis of the different tests of FAIL tools

	Results compared	Used indices
Test model vs. reality	Ranking Total number	- Mark Index - Benefit Index
Test model vs. model	Ranking Total number of failures Influencing factors	- Difference of Mark indices
Test uncompleted data model vs. complete model according to reality	Ranking Total number of failures	- Mark Index - Benefit Index - Difference of Mark indices

4.2. REL TOOLS

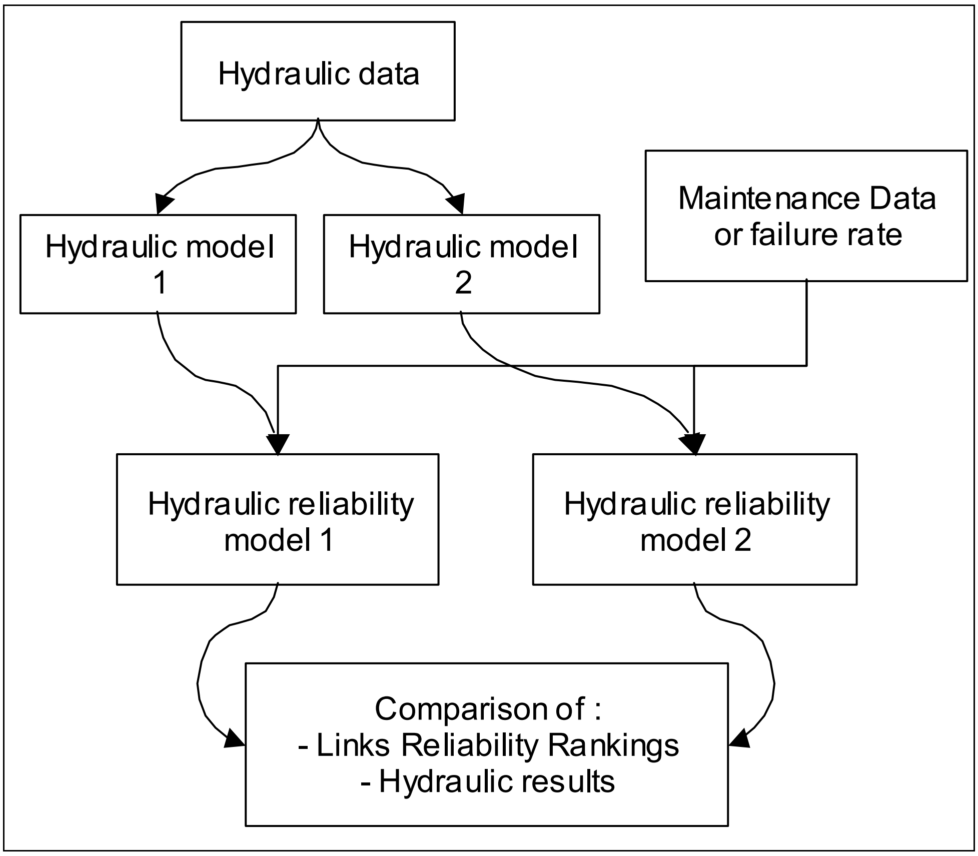

Figure 11: Comparison of Hydraulic Reliability Models

The models have been compared according to different indices (cf. Figure 11). The comparison has been done on :

- hydraulic model results

This comparison was made on important consumption nodes of each network. It aims to eventually detect causes of divergence in reliability results.

- hydraulic reliability rankings of the links.

Basic hydraulic parameters (duration, demand, desired pressure, roughness) were the same for each model.

5. THE TESTS

5.1. TESTS ON FAIL TOOLS

The tests on FAIL models have been made on 3 networks :

- Trondheim in Norway (Poisson, PHM, Winroc),
- Stuttgart in Germany (Poisson, PHM),
- Lausanne in Switzerland (PHM).

5.1.1. The data

The figures and table presented pages 25-26-27-28 describe the data used for the tests.

Installation date

Trondheim and Lausanne Networks have the same installation date profiles:

- 100 km on the total laid up to the second world war,
- a development of the networks from 1945-1950,
- a higher development in the 1960's and 1970's.

In Stuttgart, a greater part of the network was laid in 1940 (almost 30 % of the network). Just after the war, a constant length of pipe has been laid up to now.

Material

About Ductile Iron and grey cast iron, Trondheim and Lausanne have again the same description. Half of the pipes are in Ductile Iron and around 20 to 28 % are in Grey Cast Iron. For Stuttgart the grey cast iron pipes take a greater part : 45 %. This characteristic is linked to the installation date.
A characteristic of Lausanne is its high number of steel pipes (10 %).

Diameter

In the three networks, the majority diameter is 100 to 150 mm. In Stuttgart, the part of diameter between 175 and 250 is greater, due to the size of the city.

Failures by year

In Trondheim and Stuttgart, the number of failures is relatively constant for 15 years. In Lausanne, this number was constant up to 1995 and has been increasing for 5 years. This increasing is mainly linked with a better recording of maintenance data as failures and the setting up of a computer data-base.

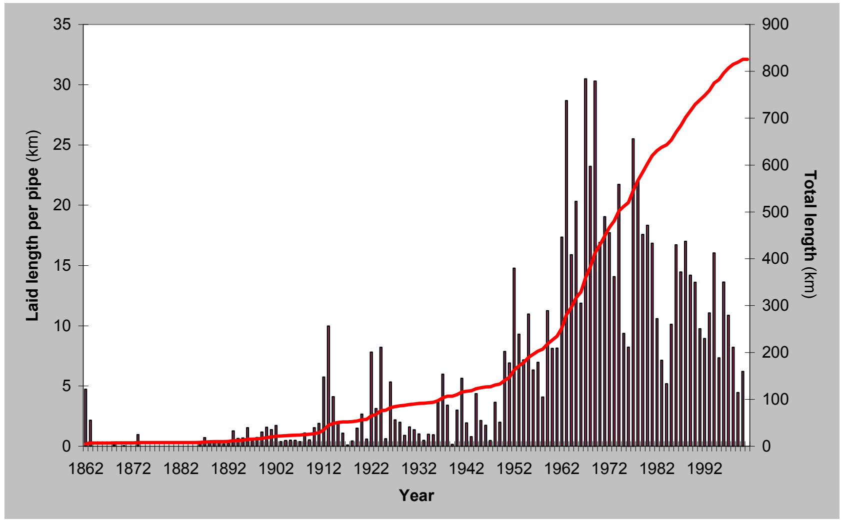

Figure 12 : Length of pipes being laid per year and the corresponding cumulative network length (Trondheim, 1988-2000)

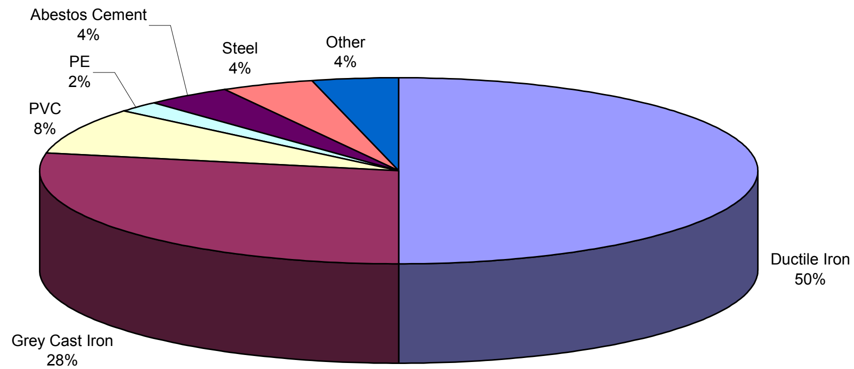

Figure 13 : Material on Trondheim water network (Trondheim, 1988-2000)

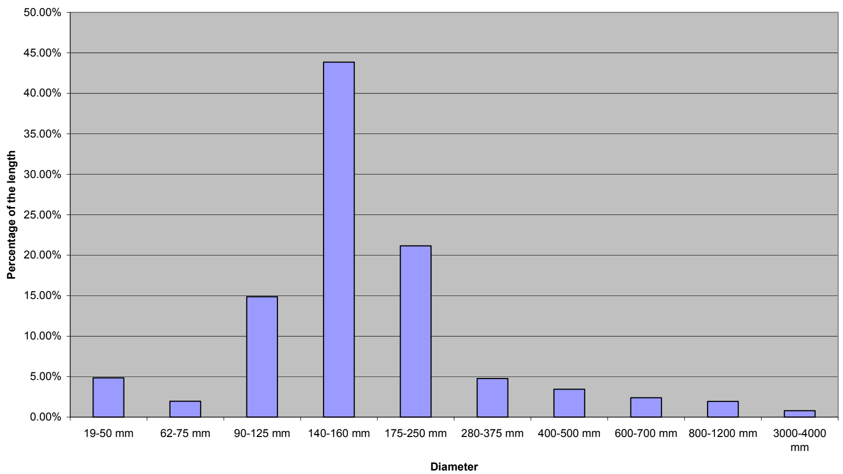

Figure 14 : Length of pipes being laid per diameter (Trondheim, 1988-2000)

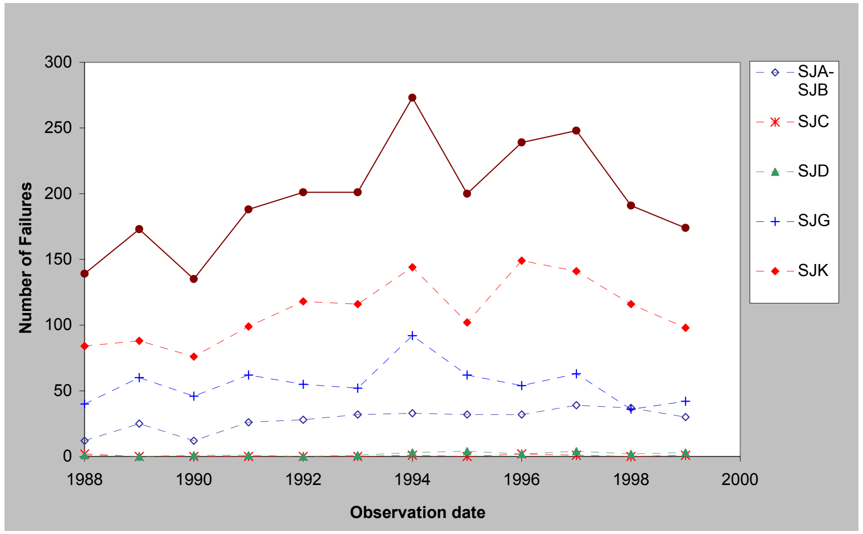

Figure 15 : Number of failures per material and year (Trondheim, 1988-2000)

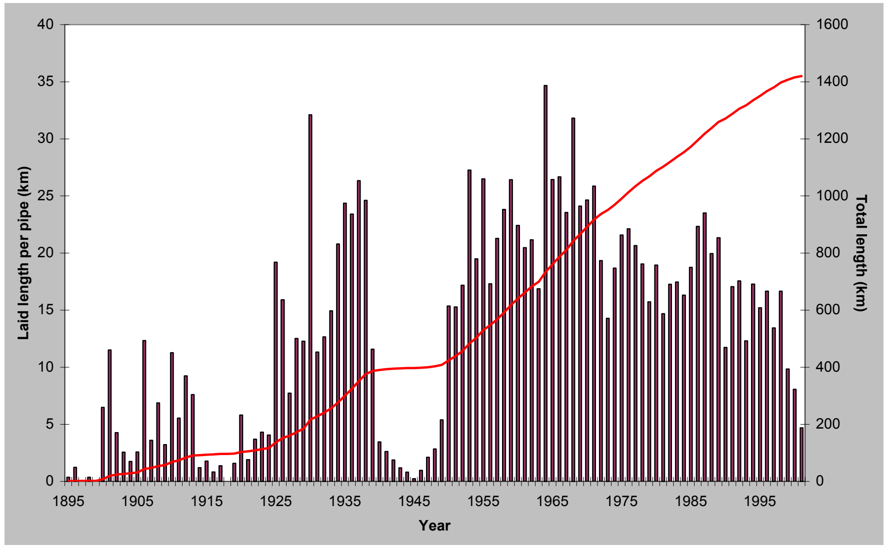

Figure 16 : Length of pipes being laid per year and the corresponding cumulative network length (Stuttgart, 1985-2000)

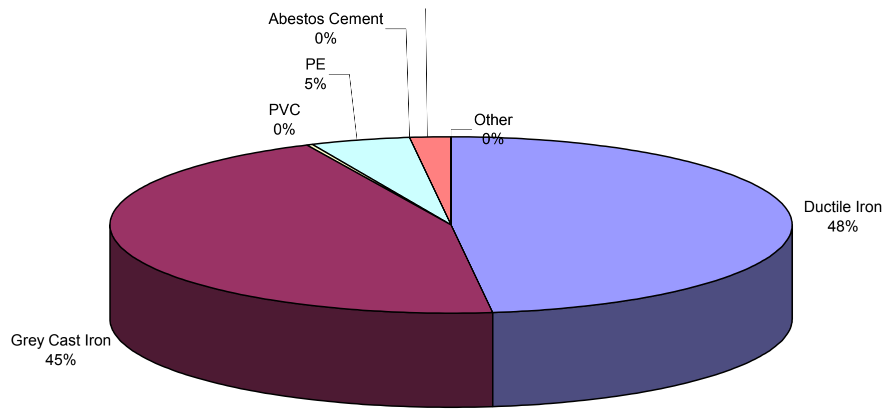

Figure 17 : Material on Stuttgart water network (Stuttgart, 1985-2000)

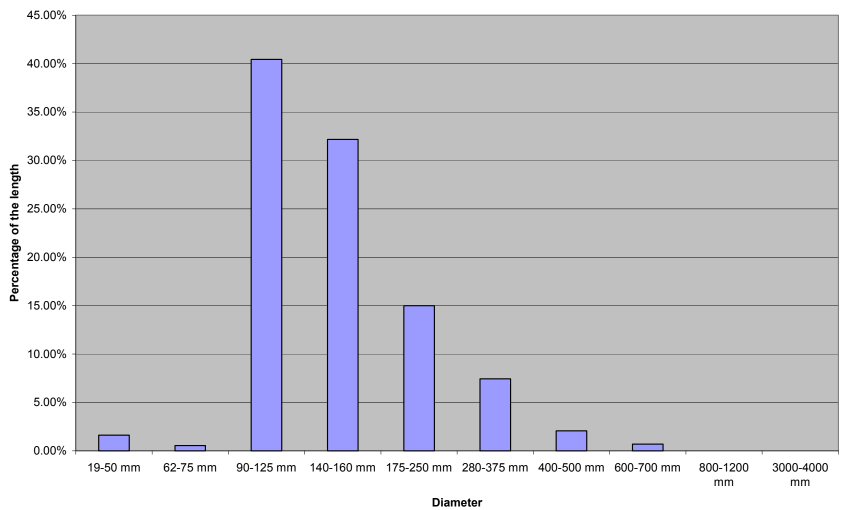

Figure 18 : Length of pipes being laid per diameter (Stuttgart, 1985-2000)

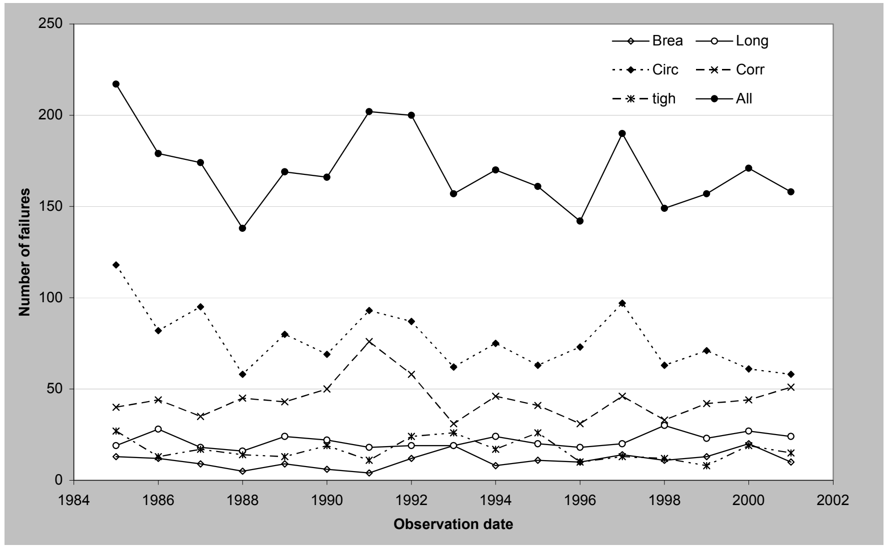

Figure 19 : Number of failures per failure type and year (Trondheim, 1988-2000)

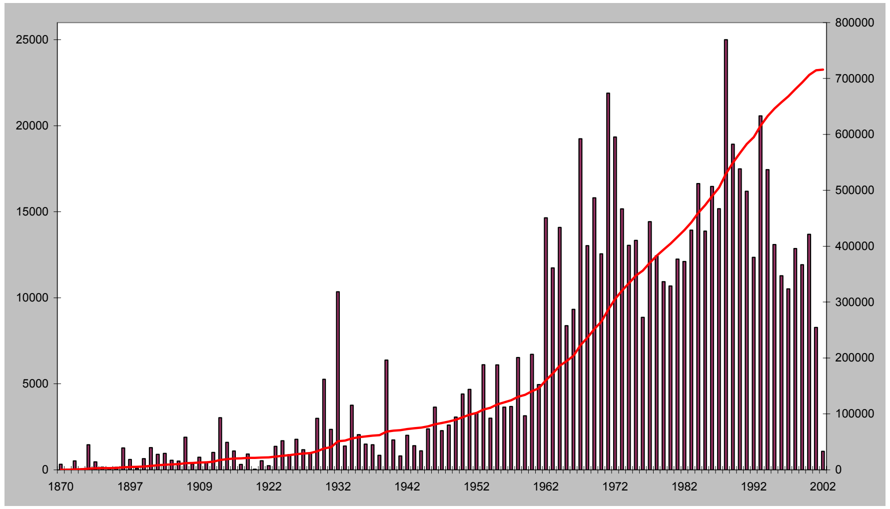

Figure 20 : Length of pipes being laid per year and the corresponding cumulative network length (Lausanne 1980-2000)

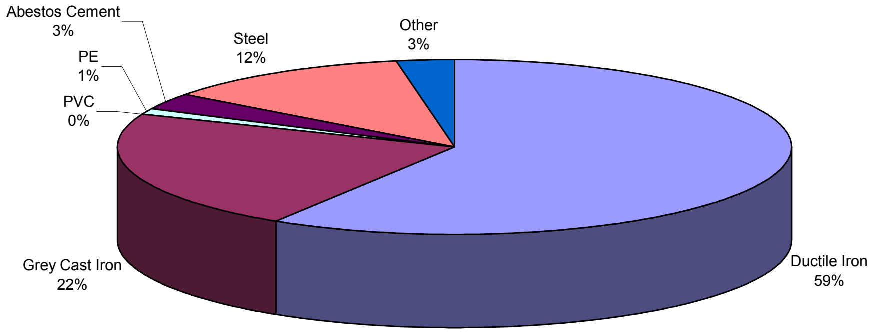

Figure 21 : Material on Lausanne water network (Lausanne 1980-2000)

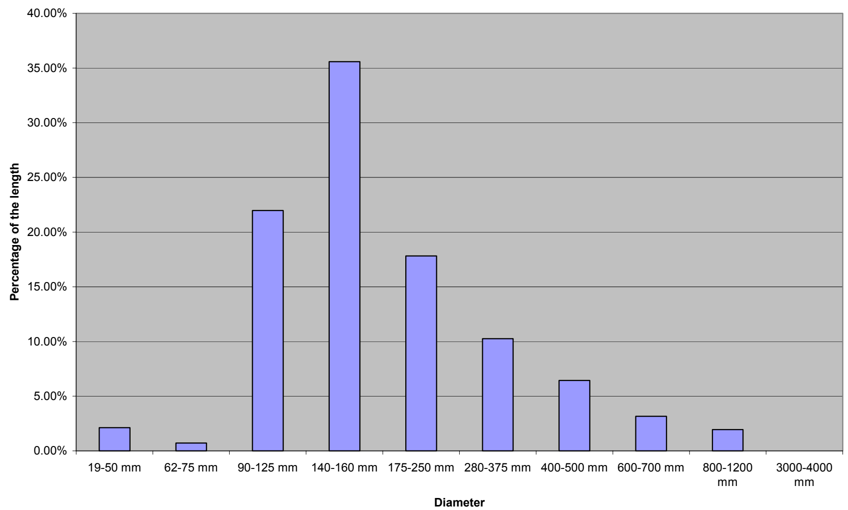

Figure 22 : Length of pipes being laid per diameter (Lausanne, 1980-2000)

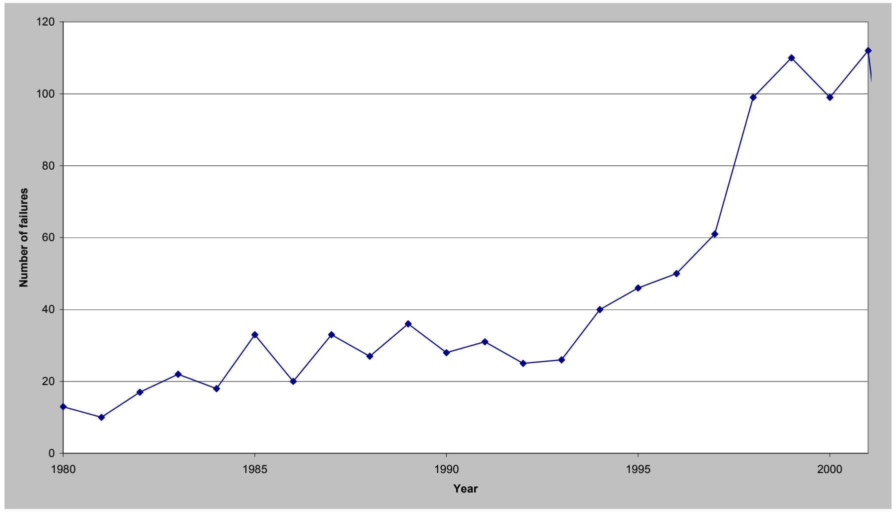

Figure 23 : Number of failures per year (Lausanne, 1980-2000)

Table 10 : Characteristics of the networks for FAIL tools tests

	Trondheim	Stuttgart	Lausanne
Length (km)	827	1424	734
Number of pipe segments	7659	19195	8126
Material	Ductile Iron (50%) Cast Iron (28 %) PVC (8 %) Steel (4%) Abestos cement (4%) +Concrete, Copper, PE	Ductile Iron (48%) Cast Iron (45 %) PE (4.8%) Steel (2%) PVC (0.2 %)	Ductile Iron (58%) Cast Iron (22%) Steel (12 %) Iron (3%) Abestos cement (3 %) PE-PVC (2%)
Diameter	19 – 4000 mm	50-1000 mm	19-700 mm
Variables	Type of soil	Internal and external protection, type of joint, observed depth, bed, corrosion, deposit, type of failure	Water pressure, Type of supply,
Failure observation time	1988-2000	1985-2000	1980-2000
Number of failures	2304	2900	980

5.1.2. Results

The performed tests were different according to the services.

5.1.2.1. Trondheim

In Trondheim, the data has been collected between 1988 and 2000 and the majority of the pipes were in ductile and grey cast iron. Consequently it has been chosen to made different tests according the duration of collected data and the material. These tests are presented in the Table 11. They had several objectives :

- assessing the influence of the considered material,
- assessing the influence of failures observation period to build the models on the results,
- assessing the influence of the observation period to be compared with the forecast on the results,
- assessing the influence of the variable soil on the results.

To assess the efficiency of the different forecast, the indices defined in parts 4.1.3 and 4.1.4 have been used.

Table 11 : Tests performed on Trondheim networks

N° test	Sample	Observation period to build the model	Observation period to be compared with forecasting	Variables
1.1	All	1988-1999	2000	All
1.2	All	1988-1998	1999-2000	All
1.3	All	1988-1995	1996-2000	All
2.1	All	1988-1995	1996-2000	All
2.2	All	1990-1995	1996-2000	All
2.3	All	1992-1995	1996-2000	All
2.4	All	1994-1995	1996-2000	All
2.5	All	1988-1995	1996	All
2.6	All	1988-1995	1996-1997	All
2.7	All	1988-1995	1996-1998	All
2.8	All	1988-1995	1996-1999	All
2.9	All	1988-1995	1996-2000	All
2.10	All	1988-1995	1996-2000	All except soil*

- **Influence of the considered material (tests 1.1, 1.2, 1.3)**

Three tests have been made :

- a test elaborated with GCI sample,
- a test elaborated with DCI sample,

- a test elaborated with DCI and GCI sample.

The results are described in Table 12.

Table 12 : Comparisons of Mark indices according to material of the sample (PHM and Poisson Model)

Mark Index	1988-1999 compared to 2000		1988-1998 compared to 1999-2000		1988-1995 compared to 1996-2000	
	PHM	Poisson	PHM	Poisson	PHM	Poisson
GCI	0.7178	0.72810	0.7295	0.73937	0.7300	0.72910
DCI	0.85585	0.84827	0.84037		0.84017	0.83112
GDCI	0.83861	0.83279	0.83956	0.82057	0.82604	0.80973

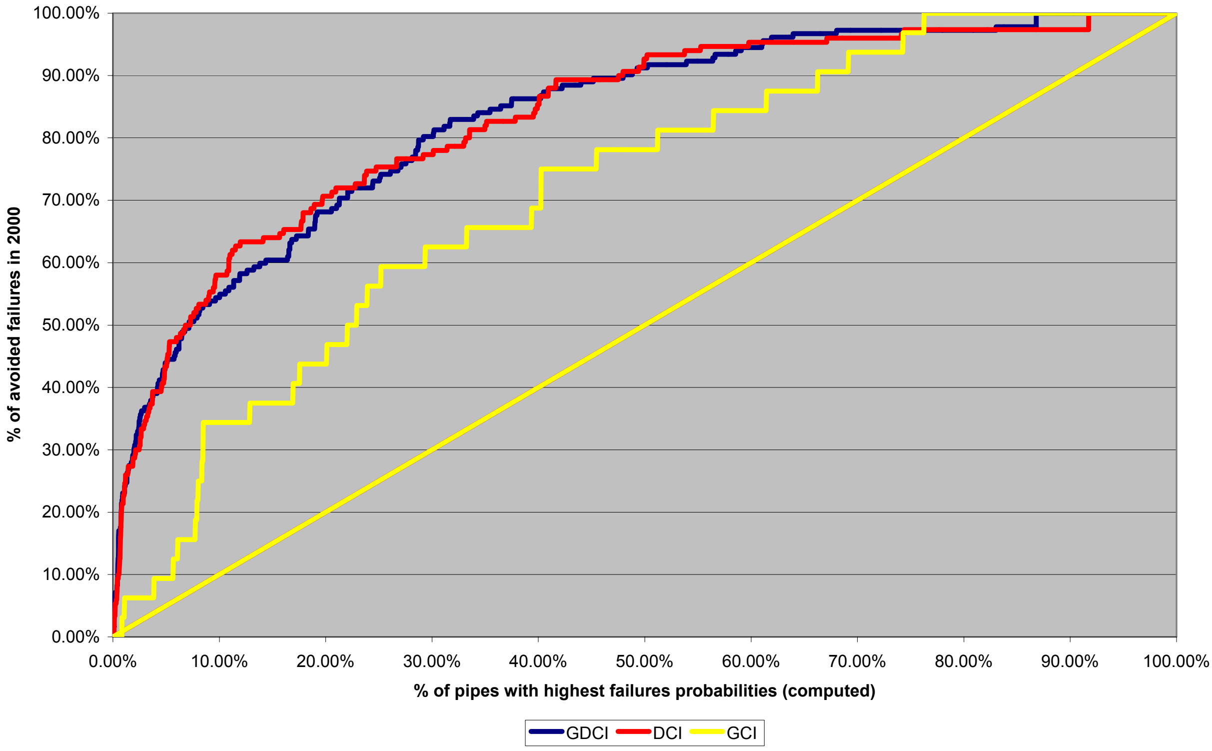

Figure 24 : comparison of Benefit indices according to material (PHM – Observation period : 1988-1999 compared to 2000)

This indices show better results for the tests made with Ductile Iron samples (for PHM as for Poisson Model). The Mark index is very high (around 0.85) and the benefit index shows that choosing 7% of the pipes with higher failures risk could allow to avoid 50% of the failures. Using DGCI samples doesn't degrade too much the results. On the other hand, GCI samples provide really worse results.

This would tend to show that the forecast is more difficult with GCI pipes. That could be caused that among the GCI pipes, only pipes in good condition do still exist.

- **Influence of the data observation period on the results (tests 2.1, 2.2, 2.3, 2.4)**

The objectives of these tests were to consider the influence of the data period on the efficiency of the results. In other words, they aimed to assess if very short period can provide good forecasts.

The Table 13 presents the results of PHM and Poisson considering several observation periods: 1988-1995, 1990-1995, 1992-1995, 1994-1995, using grey and ductile cast iron sample.

Table 13 : Results of Benefit and Mark Indices for comparison of data periods used to perform the models

		DGCI-test 2.1		DGCI-test 2.2		DGCI-test 2.3		DGCI-test 2.4	
Period for model		1988-1995		1990-1995		1992-1995		1994-1995	
Compared to		1996-2000							
% of pipes with highest predicted failure rates		% of Avoided Failures	Number of Avoided Failures	PAF	NAF	PAF	NAF	PAF	NAF
Benefit Index	1%	9.65%	87	9.09%	82	8.65%	78	7.43%	67
	2%	17.74%	160	16.19%	146	15.30%	138	15.08%	136
	5%	34.48%	311	32.48%	293	31.26%	282	25.61%	231
	10%	47.34%	427	44.90%	405	41.91%	378	37.36%	337
	25%	68.18%	615	65.63%	592	66.96%	604	62.86%	567
	50%	90.24%	814	90.24%	814	89.25%	805	87.69%	791
Mark Index	PHM	0.82604		0.81757		0.81098		0.79322	
	Poisson	0.83279		0.81183		0.81437			

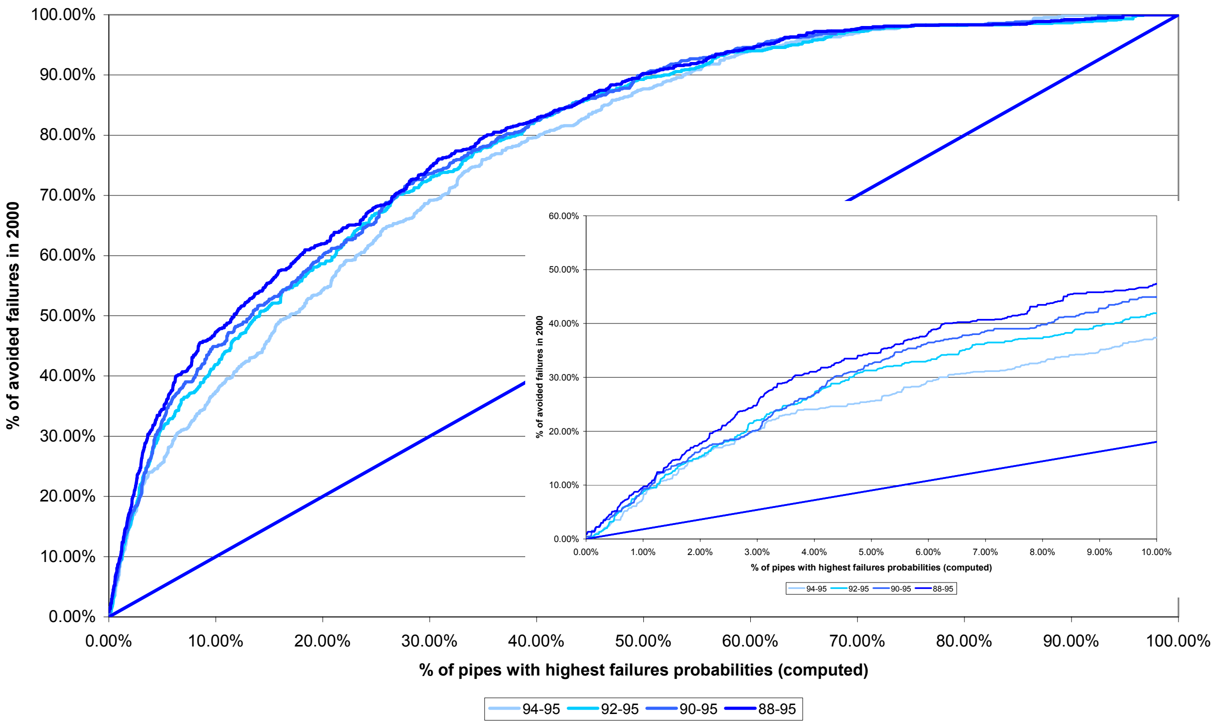

Figure 25 : Comparison of Benefit Indices according to data period used to elaborate the model (DGCI)

Figure 25 shows the benefit indices for the different period with PHM modelling.

These results show that the forecast is less efficiency with very short period (2 years). However a 2 years-observation period provides still a relatively good forecast. Indeed 5 % of the highest failure risk pipes can avoid almost 25% failures and 10% allow to avoid almost 40%.

- **Influence of period of failures observation used to be compared with the forecast of models built from fixed period (tests 2.5, 2.6, 2.7, 2.8 and 2.9)**

For the comparison, the models used were models built with observation data period 1988-1995. The failures observation periods for comparison are 1996, 1996-1997, 1996-1998, 1996-1999 and 1996-2000. Indeed it has been observed that the number of failures could vary a lot year after year because of meteorology characteristics variation.

Table 14 : Results of Benefit and Mark Indices for comparison of period of failures observation to be compared with the forecast

		DGCI-test 2.5		DGCI-test 2.6		DGCI-test 2.7		DGCI-test 2.8		DGCI-test 2.9	
Period for model		1988-1995									
Compared to		1996-2000		1996-1999		1996-1998		1996-1997		1996	
% of pipes with highest predicted failure rates		% of Avoided Failures	Number of Avoided Failures	PAF	NAF	PAF	NAF	PAF	NAF	PAF	NAF
Benefit Index	1%	10.31%	93	8.69%	63	10.23%	59	10.98%	46	12.61%	28
	2%	17.63%	159	16.69%	121	17.85%	103	20.53%	86	20.72%	46
	5%	35.25%	318	33.66%	244	36.57%	211	36.04%	151	37.84%	84
	10%	47.23%	426	47.31%	343	49.39%	285	51.31%	215	56.76%	126
	25%	69.84%	630	66.62%	483	69.32%	400	68.02%	285	72.07%	160
	50%	90.47%	816	89.66%	650	87.87%	507	87.35%	366	89.19%	198
Mark Index	PHM	0.82710		0.81780		0.81817		0.81380		0.82892	
	Poisson	0.83279		0.80167		0.80097		0.79850		0.74178	

The results are different according to the used models.

For Poisson, shorter is the period worse are the results (from 0.83 to 0.74). For PHM, the length of the period doesn't seem influence the Mark index.

- Influence of the variable "soil" on the forecast.

The environmental variable "soil" was available in Trondheim network. These tests aimed to assess the influence of this variable. For each model, two tests have been applied, with and without the variable "soil".

The Table 15 and Figure 26 show the results of the tests.

Table 15 : Results of Benefit and Mark Indices for comparison of period of failures observation to be compared with the forecast

	PHM		Poisson	
Period for model	**1988-1995**			
Compared to	**1996-2000**			
Benefit Index	**with soil variable (test 2.1)**	**without soil variable (test 2.10)**	**with soil variable (test 2.1)**	**without soil variable (test 2.10)**
% of pipes with highest predicted failure rates	**% of Avoided Failures**	**% of Avoided Failures**	**% of Avoided Failures**	**% of Avoided Failures**
1%	10.31%	9.98%	3.39	3.35
2%	17.63%	17.96%	10.06	10.27
5%	35.25%	34.04%	26.44	28.24
10%	47.23%	46.78%	44.07	44.43
25%	69.84%	69.40%	68.14	68.75
50%	90.47%	89.80%	88.47	86.61
Mark index	0.82710	0.82581	0.83279	0.80517

The mark index provides a little improvement by considering the variable "soil" for PHM as for Poisson. However the benefit index doesn't show an evident improvement especially for the pipes with highest failures risk. Variable soil contributes mainly to distinguish the pipe with low failure risk, i.e. without previous failures.

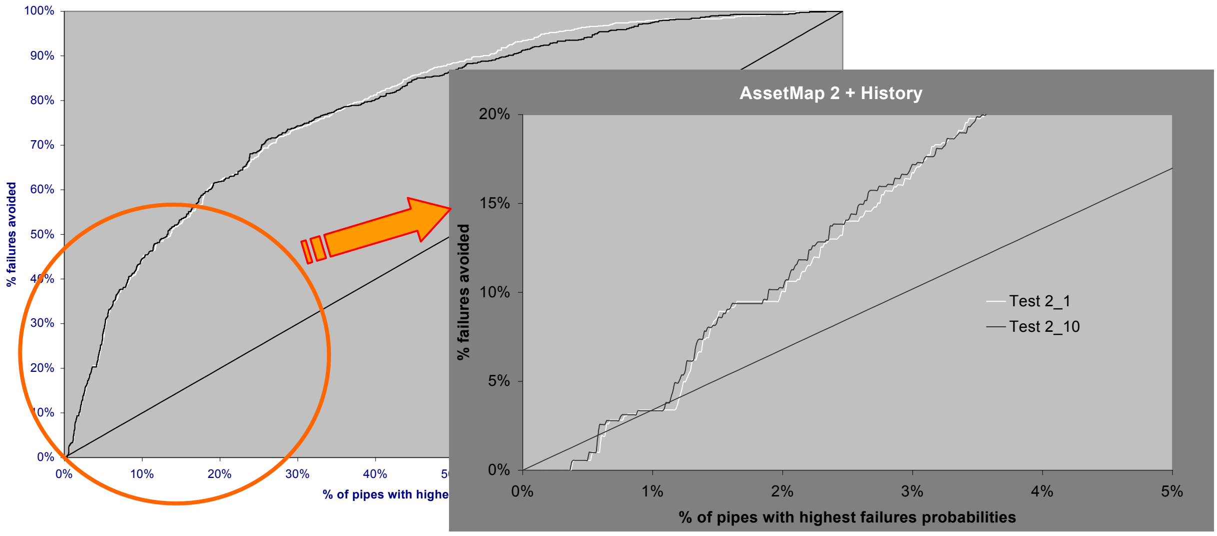

Figure 26 : Comparison of Benefit curves, using or not soil variable (Poisson, model 1988-1995 compared to 1996-2000)

5.1.2.2.Stuttgart

In Stuttgart the data have been collecting since 1985 and recorded in a computer data-base. One specification of the data is the distinction between the several types of repair : pipe break or leak (no longitudinal, no circular), Longitudinal break, Circular break, Corrosion, non-Tight join.

One other specification is the existence of data describing the pipe after opening the trench because of failure. These data were however difficultly useable, because they could cause a statistical bias.

The last specification was that no environmental data was available.

The tests concerning Stuttgart were as following, with different objectives :

- Comparison of the types of failure,
- Comparison of the results of forecast according to the length of failure history,
- Comparison of the results according to the period used for the comparison.

- tests according to the type of failures :

The tests presented in the Table 16 have been performed. These are distinguished by the type of failures. In this part, tests on specific material as steel or PE-PVC have also been performed. These are concerning all the failures because of the little size of the sample of this material.

Table 16 : tests performed in Stuttgart, according to the type of failures

Sample pipe (Material)	Failure sample	Historic for model	Length (km)	Failure numbers
DI-CI	Corrosion failures on pipe	1985-2001	20.065	355
DI-CI	Circumferential failures on pipe	1985-2001	20.065	841
DI-CI	Longitudinal failures on pipe	1985-2001	20.065	190
DI-CI	Failures on pipe	1985-2001	20.065	1477
DI-CI	Failures on joint	1985-2001	20.065	163
Steel	All failures	1985-2001	0.304	55
PE-PVC	All failures	1985-2001	0.422	55

Table 17 presents a synthesis of the significant variables of the Poisson model according to the type of failures. It gives several indications:

- The failures due to corrosion appear mainly for the little diameter pipes and aged between 20 and 30 years. Indeed the pipes more than 30 have less corrosion than 20 to 30 years. This shows this more linked to a specific laid period than to the ageing of the pipes.
- The circular breaks appear mainly on little diameter pipes in Grey Cast Iron.
- On the other hand, longitudinal breaks appear on large pipes in Ductile iron.
- Globally failures on pipe appear on aged little pipes in Grey Cast Iron and failures on joint are mainly linked to the age of the pipes.

- Tests according to the period length of data record

First a comparison between several forecasts depending on the length of duration data historic used for model has been made. The results of Mark indices are presented in the Table 18 .

It shows that Poisson model gives, with Stuttgart data, better results. About Poisson, Mark Indices are decreasing lightly according to the history but still at a really acceptable level.

On the contrary PHM model provides worse results than tests on Trondheim network, but with an improvement using very short data records (1994-1995). This seems to indicate that, in the case of Stuttgart, very recent maintenance data is most instructive than longer records. One reason of this result is that, after a defined number of failures a pipe is systematically replaced in Stuttgart.

Table 17 : Significant variables according to the type of failure (Poisson Model, Stuttgart)

<table>
<tr><td>Material</td><td>DI-CI</td><td>DI-CI</td><td>DI-CI</td><td>DI-CI</td><td>DI-CI</td><td>Steel</td><td>PE – PVC</td></tr>
<tr><td>Type of failures</td><td>Corrosion</td><td>Circular</td><td>Longitudinal</td><td>Pipe failures</td><td>Joint failures</td><td>All failures</td><td>All failures</td></tr>
<tr><td>Diameter</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td><= 80</td><td rowspan="3">1</td><td rowspan="2">1</td><td rowspan="3">1</td><td rowspan="2">1</td><td rowspan="4">/</td><td rowspan="3">1</td><td rowspan="4">/</td></tr>
<tr><td>] 80-100]</td></tr>
<tr><td>] 100- 150]</td><td>0.484</td><td>0.764</td></tr>
<tr><td>> 150</td><td>0.481</td><td>0.224</td><td>1.856</td><td>0.362</td><td>0.359</td></tr>
<tr><td>Material</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>CI</td><td rowspan="2">/</td><td>1</td><td>1</td><td>1</td><td>1</td><td rowspan="4"></td><td rowspan="2"></td></tr>
<tr><td>DI</td><td>0.112</td><td>31.075</td><td>0.343</td><td>/</td></tr>
<tr><td>HDPE PE PVC</td><td colspan="5" rowspan="2"></td><td>1</td></tr>
<tr><td>MDPE</td><td>0.252</td></tr>
<tr><td>Age</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>[0-10]</td><td>1</td><td rowspan="2">1</td><td rowspan="5">/</td><td>1</td><td rowspan="4">1</td><td rowspan="5">/</td><td rowspan="2">1</td></tr>
<tr><td>]10-20]</td><td>3.169</td><td>2.532</td></tr>
<tr><td>]20-30]</td><td>10.644</td><td>10.113</td><td>9.001</td><td>2.600</td></tr>
<tr><td>]30-40]</td><td rowspan="2">6.159</td><td>9.052</td><td>7.405</td><td rowspan="2">2.488</td></tr>
<tr><td>> 40</td><td>9.810</td><td>9.278</td><td>3.461</td></tr>
</table>

Table 18 : Comparison of Mark indices from Poisson and PHM forecasts, according to data historic duration (Data from Stuttgart Water Supply)

Data period for model	Compared to observed period	Poisson	PHM
1985-1995	1996-2000	0.81868	0.71645
1990-1995	1996-2000	0.81230	0.67471
1994-1995	1996-2000	0.80869	0.77376

The Figure 27 is presenting Benefit indices for PHM and Poisson using 1985-1995 data. This shows the difference between the two models. For instance, considering the 10% percent of pipes with highest failure risks allows to avoid failures 40% of failures with Poisson and 35% of failures with PHM.

- Tests according to the observed data used for the comparison

The Table 19 presents the results of Mark indices concerning these tests. For Poisson the indices show results as good as for the previous tests. For PHM, results show a tendency to better results with the decreasing of period of observed data.

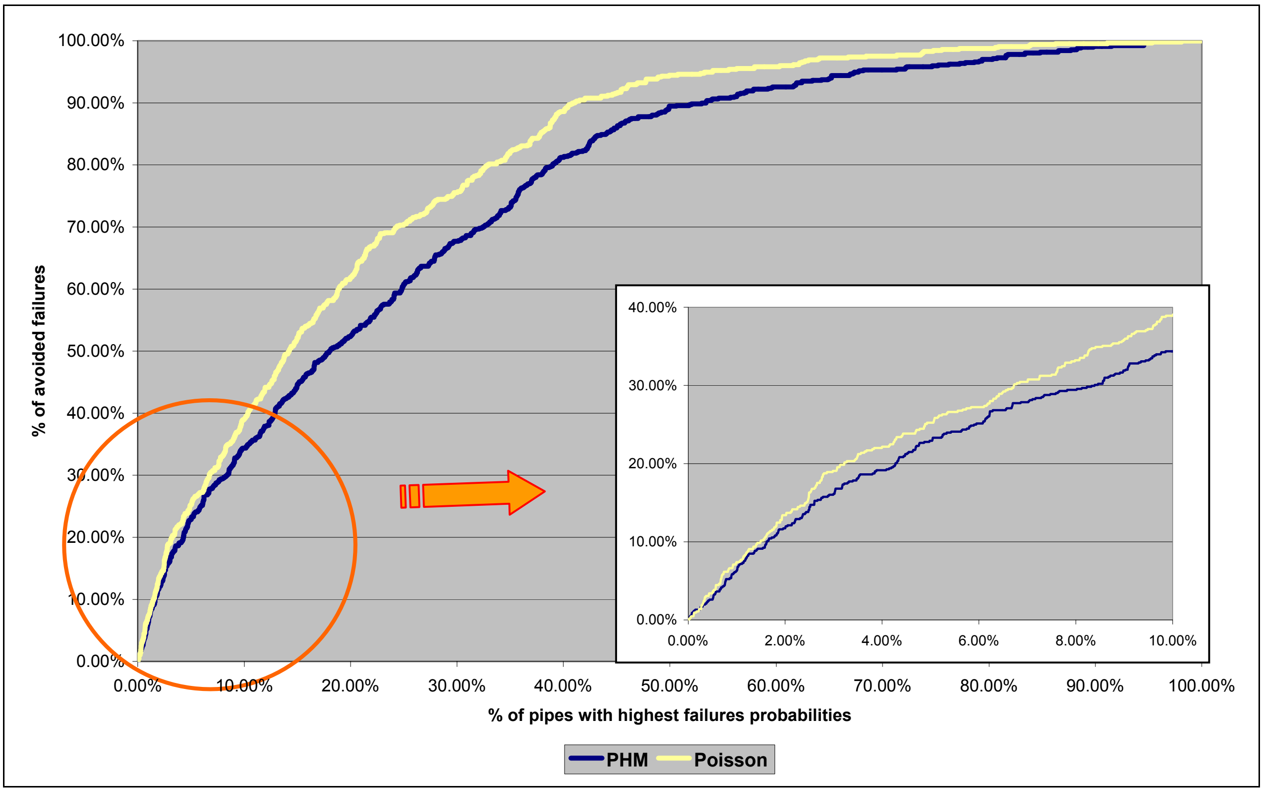

Figure 27 : Benefit Indices for PHM and Poisson Models (data used for models : Stuttgart – 1985-1995)

Table 19 : comparison of Mark indices according to observed data used for comparison

Data period for model	Compared to observed period	Poisson	PHM
1985-1995	1996-2000	0.81868	0.71645
1985-1998	1999-2000	0.82209	0.79641
1985-1999	2000	0.81614	0.79930

5.1.2.3. Lausanne

In Lausanne data have been collected officially since the creation of the service. But it has been observed that before 1980 the failure rate was very low and completely different than in the years after 1980. The considered period of maintenance is then 1980-2000. The evolution of failure rate shows also an important increasing after 1995.
This increasing can be justified by the setting-up in 1995 of a computer data-base. In the tests below the comparison of the models for the period 1980-2000 and 1995-2000 has been made.

Compared to previous studies, two specific variables are significant. These are :

- the role of the pipe (supply or transport) for steel pipes,
- the pressure in the pipe for Cast iron pipes.

The tests performed in Lausanne are presented in the Table 20 :

Table 20 : Tests performed in Lausanne (PHM model) and Mark Indices

Historic for model	Historic for comparison	Material	Mark Index
1980-1998	1999-2001	Grey and ductile cast iron	0.824
1995-2000	2001	Grey and ductile cast iron	0.838
1980-1998	1999-2001	Steel	0.788
1995-2000	2001	Steel	0.862

The Table 20 presents also the results of the tests on Mark indices. This shows corrects values for the different model (between 0.79 and 0.86). This shows also an improvement of the indices with models elaborated on shorter period. This results confirmed that the data are more reliable for more recent period.

Benefit indices confirm these results (cf. Figure 28 and Figure 29).

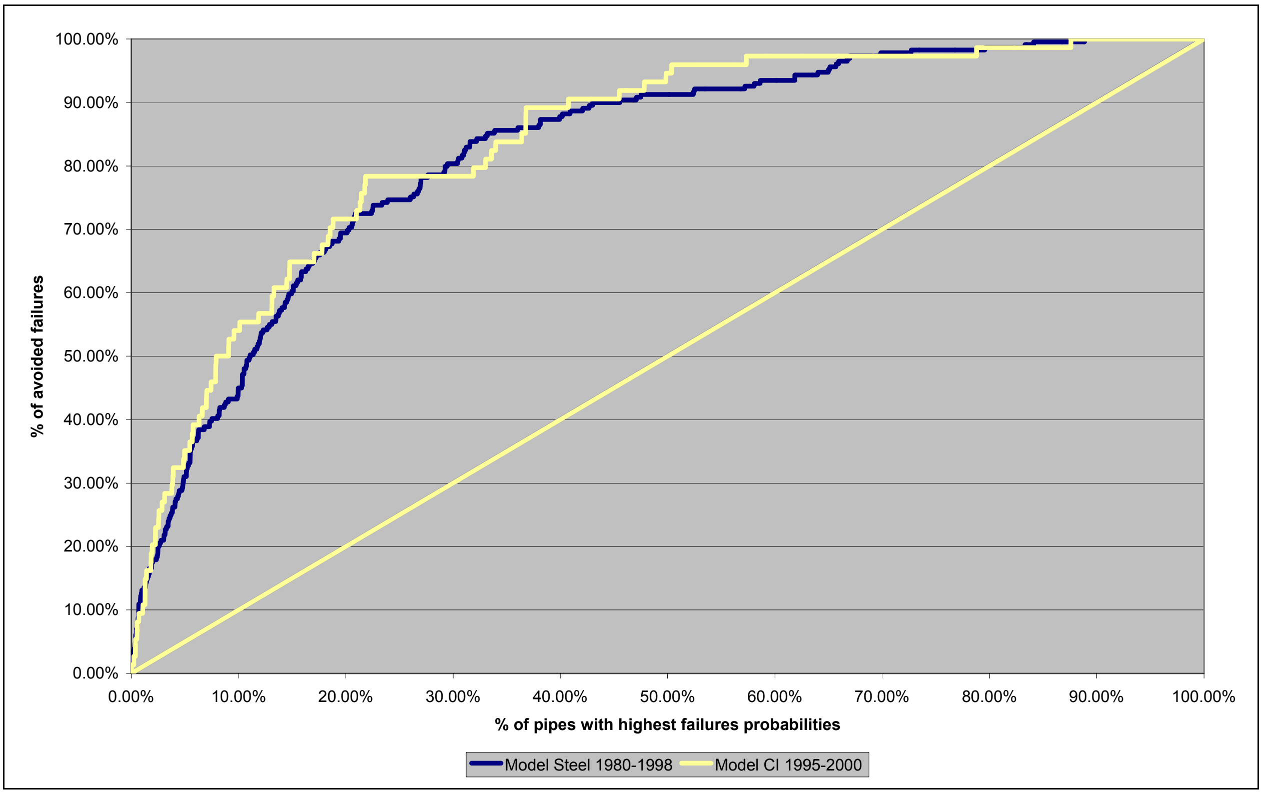

Figure 28 : Benefit indices of PHM models performed on Lausanne Water Supply (Cast iron, period of comparison : 1995-2000 and 1980-1998)

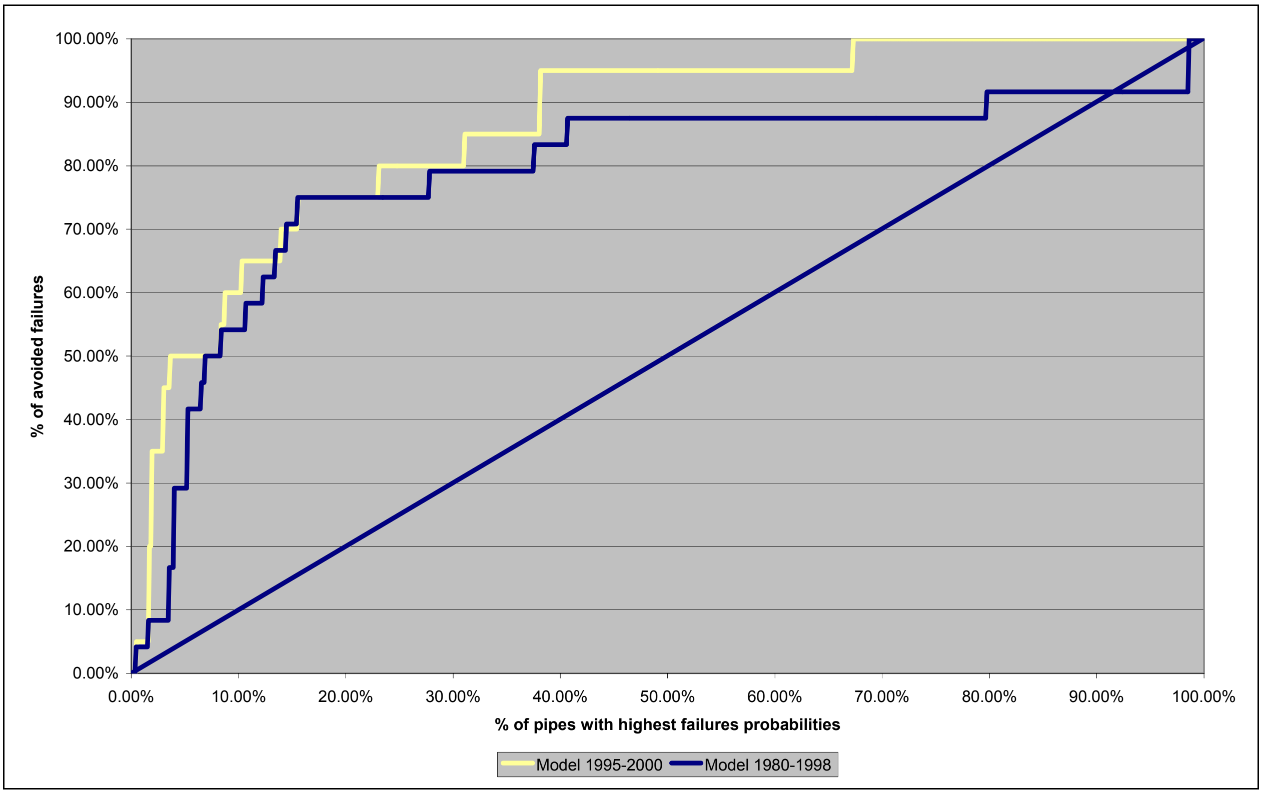

Figure 29 : Benefit indices of PHM models performed on Lausanne Water Supply (Steel, period of comparison : 1995-2000 and 1980-1998)

5.1.3. Conclusion

Firstly the tests made on the different networks have shown that the FAIL tools (Poisson and PHM) can bring to the water supply benefits concerning the choices of the pipes in the frame of annual rehabilitation program. Notably it has been shown that in some of the cases, choosing 10% of the pipes declared as with the highest failure risks could allow to avoid 50% of futures failures. These benefit indices could be fitted considering the criteria defined in ARP module and that used failure rate or failure forecast in their calculation (Repair costs, disturbances, etc…).

Secondly the influence of the existing data has been assessed. The variation of the data maintenance period used to build the model shown several results :

- long maintenance data period doesn't give always suitable results.

  This is due first to the disappearance and the replacement of pipes, which were in bad condition and included in rehabilitation programs. Consequently short maintenance data will show a better image of actual pipe condition. Last, because of the setting up of GIS or computer data-base, the data are better recorded and in a more rigorous way.
- the consideration of environmental variable

  Only one test has been done. This concerned the soil considered on Trondheim networks. This didn't show a real improvement of the forecast even if the mark index was lightly higher with considering the variables. However the type of variable could interesting to measure the ageing of the pipe and define on long term period the lifetime of a pipe.

Third concerning the significant variables, the tests confirmed the results of previous studies : the length, the material, the installation period, the diameter and the number of previous failures has almost always significant, with a relative risk close to values assessed previously.

Fourthly in one case (Stuttgart with PHM model), results were less efficient than in other networks. The reasons of this results was not very obvious. It has been assumed that it was possibly due to a rehabilitation policy existing in the service for now a long period (20 years) with strict rules to replace pipes, that means that pipes in bad condition are still existing.

Fifthly a comparison made with simple classification of the pipes according number of previous failures and diameter has shown that this kind of "simple model" could give also interesting results. However this type of approach doesn't allow an efficient calculation of future failures useful to assess the criteria of ARP, notably because of an uncertainty higher than Poisson and PHM. More over this approach doesn't allow to differentiate the pipes on long term approach

5.2. TESTS ON REL TOOLS

5.2.1. The data

5.2.1.1.Ugla

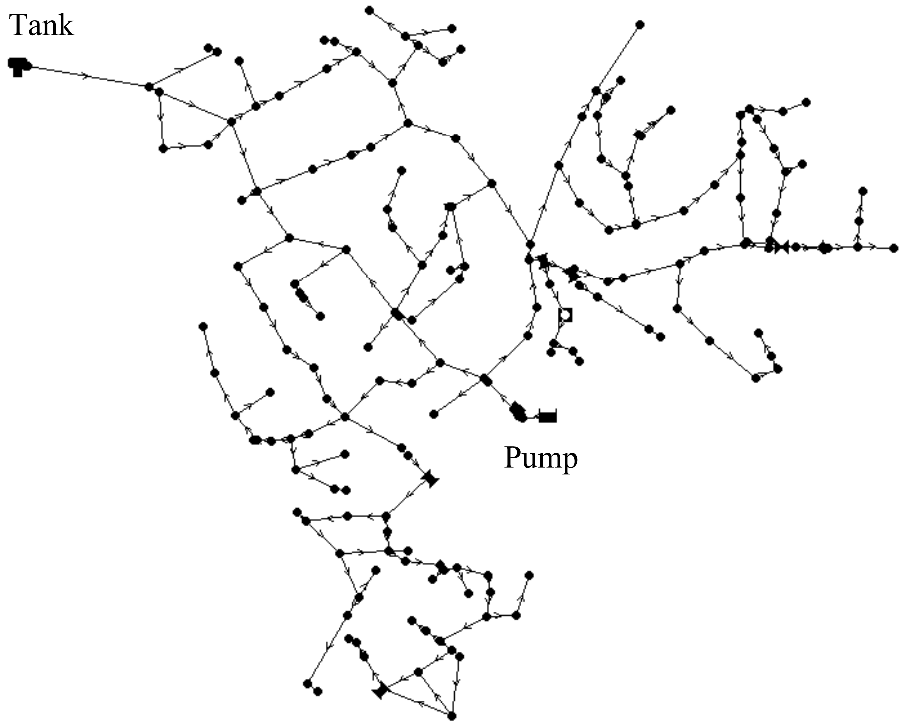

Figure 30. Illustration of the water zone Ugla in Trondheim.

The Ugla zone is a small zone in Trondheim. The zone consists of 201 pipes, a tank and a pumping station. In order to make computable the zone hydraulic, a reservoir has been included in the model downstream the pumping station (supplying the pumps). In reality there is no reservoir located here. At the border of the zone there are several closed pipes. These pipes are closed under normal operations. These pipes lead into another pressure zone. If needed (e.g. in case of pipe failure), these pipes can be opened manually by the operating crew.

For the reliability simulations it is assumed that the pressure should be more than 25 meters (100% pressure). The reliability analysis is also carried out for the peak demand of water consumption. The maximum demand factor is 1.3. All the analysis starts with this flow as the initial condition (i.e. in case of extended time simulations).

5.2.1.2. Crissier

Figure 31. Illustration of the water zone Crissier in Lausanne.

Crissier is a water zone of Lausanne water supply. It is made up of :

- 1130 pipes,
- 996 nodes,
- 1 tank.

Two parts of the network are distinguished :

- a urban part, more dense and looped,
- a semi-urban, less dense.

5.2.2. Results

For each test, two computation assumptions have been made :

- for the pressure : desired pressure for each node is equal to 25 m (or 2.5 10^5 Pa),
- for the demand : for model made on one time step, the water demand is equal to the hourly maximal demand.

Last to evaluate the unavailability time of a pipe, linked to a failure, the assumption presented in Table 21 has been made. This signifies that the repair time of a pipe depends on the diameter. This assumption could be sharpened according to other factors like, for instance, the pressure or the traffic in the street and according to the knowledge of water supply personnel.

Table 21 : Repair times for pipes in Trondheim

Pipe diameter (mm)	Repair times (hours)	
	Mean Time To Repair (MTTR)	**1% TTR**
< 300	8	24
300-400	16	48

5.2.2.1.Ugla

- **Aquarel (SINTEF) (see Appendix)**

For Aquarel three simulations have been made :

1. Aquarel with the effect of tanks but with constant water consumption in each node (default Epanet)
2. Aquarel with the effect of tanks and with sprinklers ([emitters]) in each node allowing for pressure dependent water consumption (to be compared to Failnet-Reliab)
3. Aquarel without the effect of tanks but with constant water consumption in each node (old Aquarel version) (in order to compare with the other models)

In these three simulations it was possible to classify the consumption nodes according to the availability of water. The Figure 32 shows the 20 weakest nodes according to this availability. These nodes are :

- nodes located closed to tanks,
- nodes located on branches.

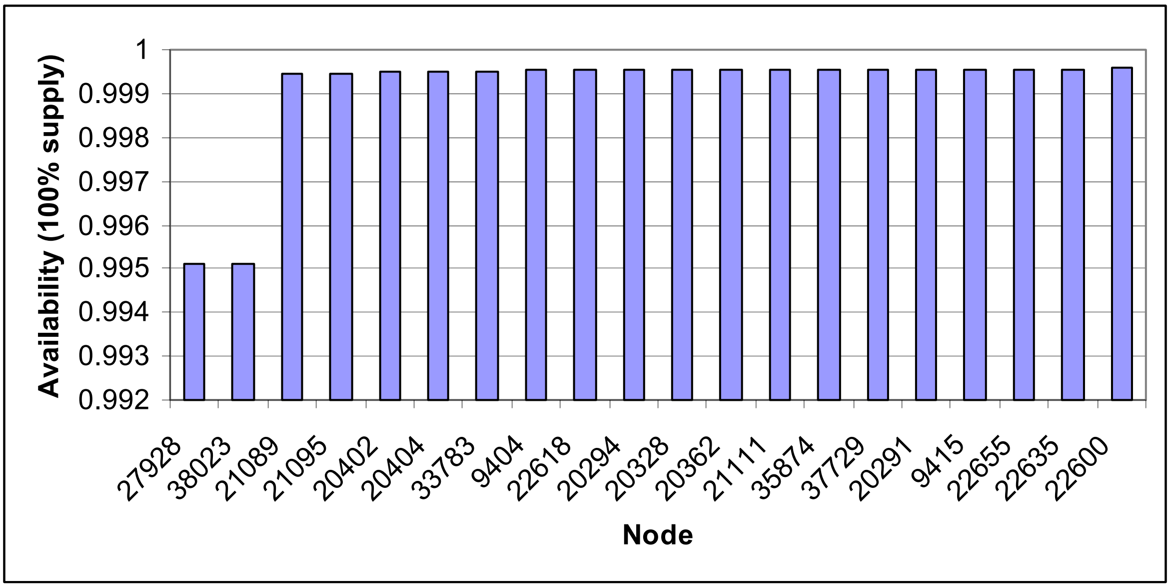

Figure 32 Availability of the 20 “weakest” nodes

Concerning the importance of the pipes, the results are different according to the tests.

For the test with effect of tanks and constant node consumption, the pipes considered as the most important are pipes located near the tank (Cf. Figure 33).

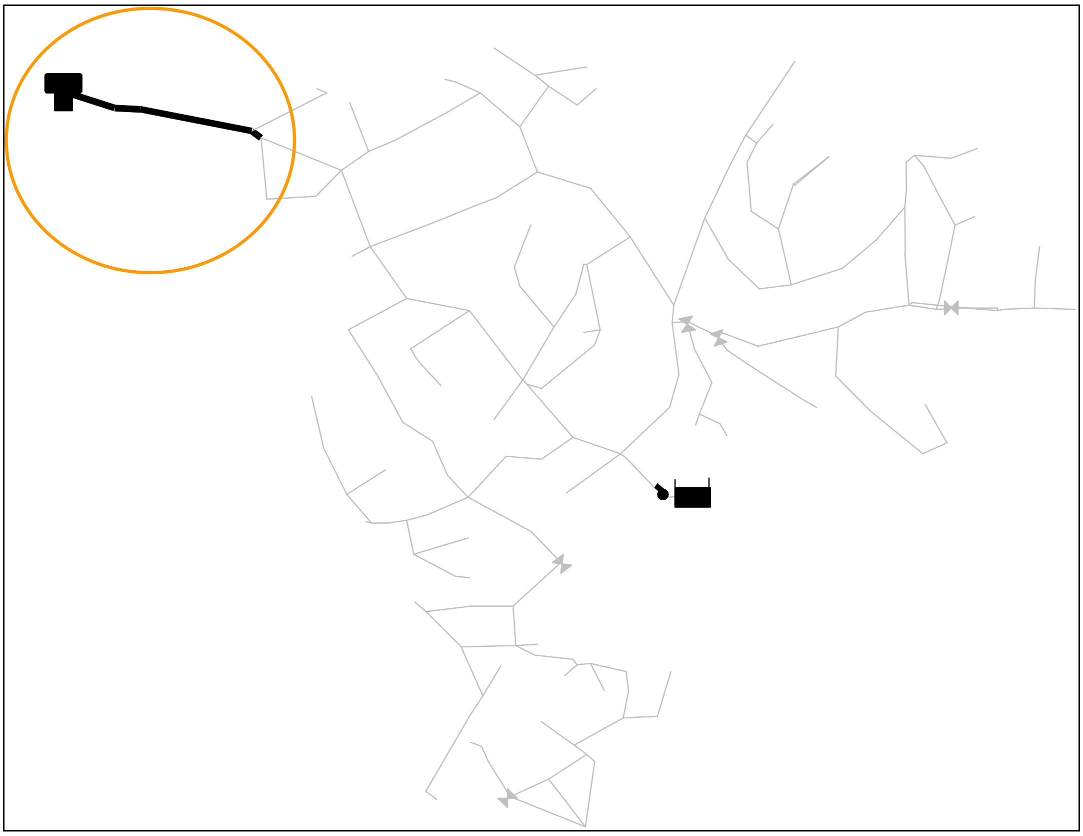

Figure 33 : Important pipe for Aquarel model (with effect of tanks, constant consumption)

For the tests with effect of tanks and with sprinklers (simulating pressure dependent consumptions), the important pipes are different. These are mainly the pipes at the beginning of branches.

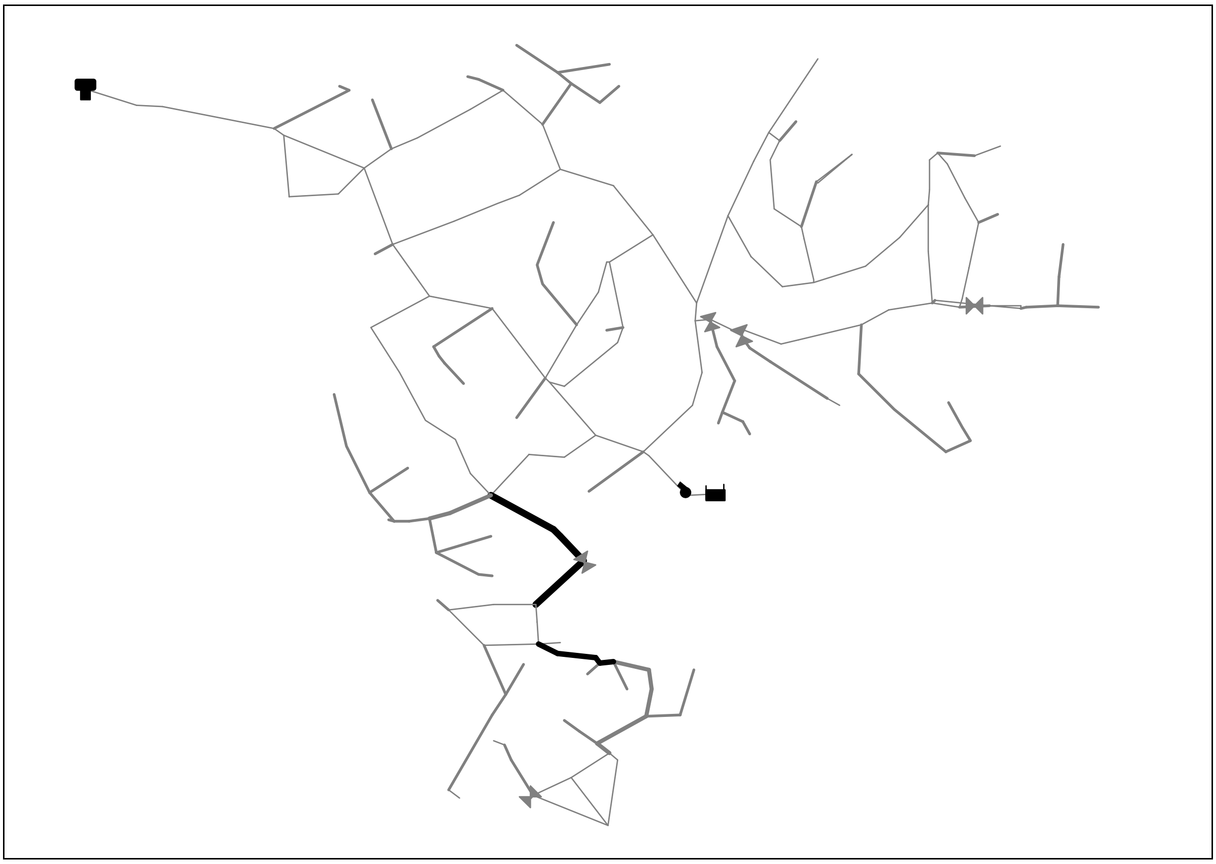

Figure 34 : Important pipes for Aquarel model (with effect of tanks, sprinklers)

To conclude, the different important measures are calculated and ranked with respect to each measure. The unavailability measure and the frequency importance measure reports for this network the same relative ranking. The Aquarel version without sprinklers reports more or less the same ranking of the pipes. The most important pipes are the pipes downstream from the tank. When sprinklers are included in the simulations a more sophisticated picture appears. Important pipes are than also discovered in the southern part of the network. These pipes are typically the mains into a smaller closed loop in the network.

- **Failnet-Reliab**

Two types of results, useful for Annual Rehabilitation program, are proposed with Failnet-Reliab. These are :

- results concerning pipe, giving an hydraulic criticality index, considering at the same time, the effect of the failure of the pipe and its failure risk,
- a global reliability index, defining the global hydraulic vulnerability of the network linked to failures.

Moreover it is possible to include failure risk forecasted from FAIL tools.

On Ugla Networks, results were close to Aquarel results with sprinklers (Cf. Figure 35). Vulnerabilities of the nodes have also been assessed and are presented on this Figure. It shows that the most vulnerable nodes are :

- nodes located on the branches,
- nodes located near to the tank, because of their elevation close to tank water level.

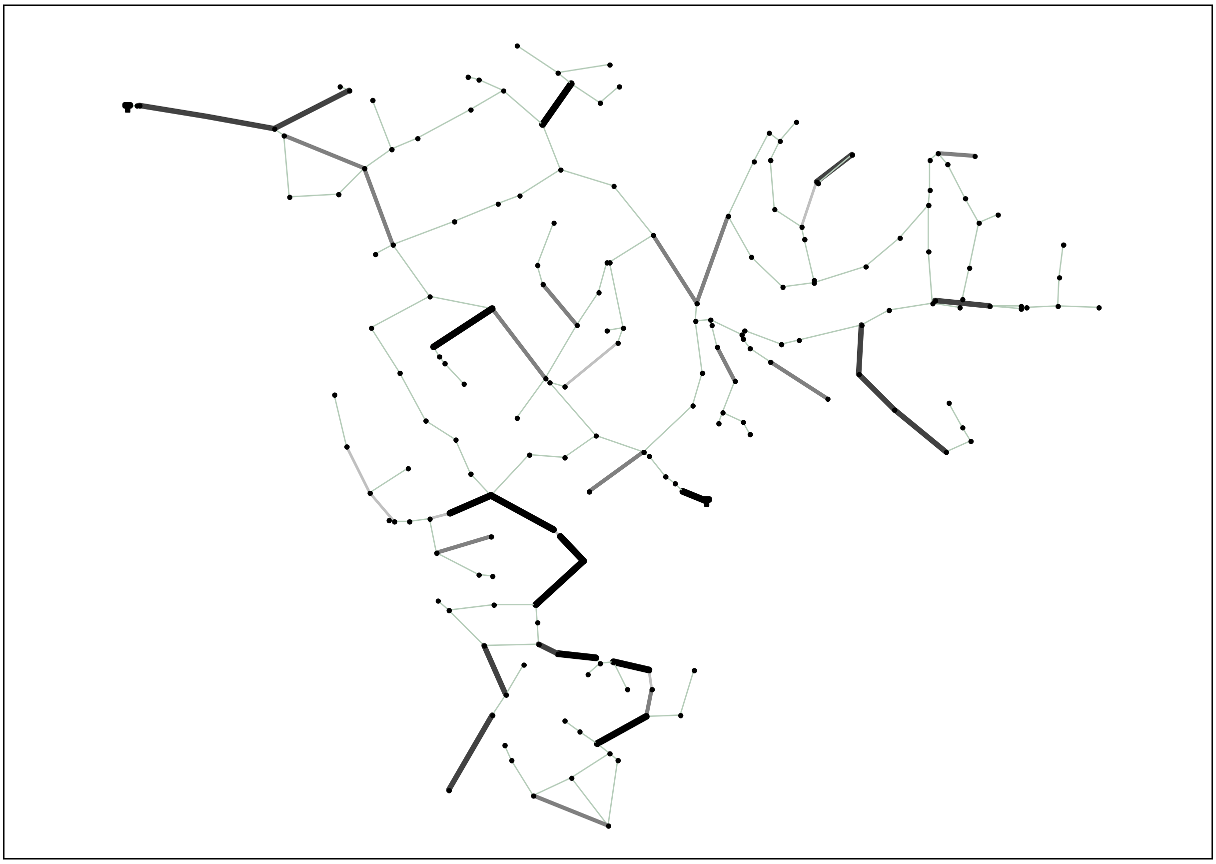

Figure 35 : Failnet-Reliab results on Ugla zone (thickness and darkness of the pipe defines its importance)

The results of Figure 35 have been computed with a constant failure rate for all the pipes. If forecasted failure rates for each pipe are considered in the computation, the results are sensitively different (Cf. Figure 36). It shows at the same time pipes which have an high hydraulic importance and which have high failure risks.

However it must be noted that this network is very reliable. Indeed the maximum HCI index is equal to $1.02\ 10^{-5}$ for the first case and $2\ 10^{-4}$ for the second case. This is confirmed by the values of global reliability index that is equal to 0.974. This shows a network with a high number of loops, which is moreover supplied by 2 tanks.

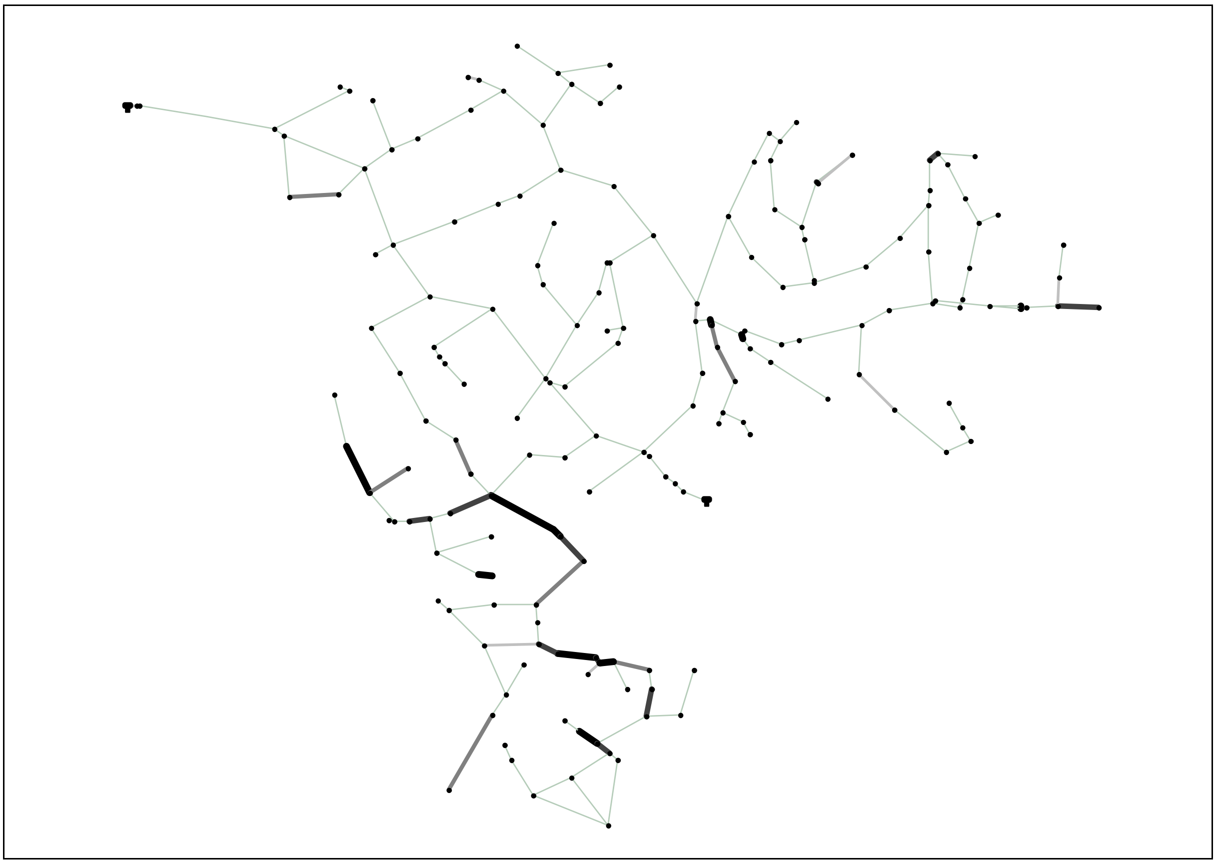

Figure 36 : Failnet-Reliab results on Ugla zone considering specific failure rates by pipe (thickness and darkness of the pipe defines its importance)

- Relnet

Relnet results on Ugla zone are presented in the Table 22. It shows that, as for Aquarel with constant consumption, the most important pipes are pipes located near to the tanks, and at the lower level, the pipes located at the beginning of the branches.

Table 22 : the 20 worst pipes according to their hydraulic importance (Relnet)

Pipe section ID	Ph14b
12899	1.00000000
184539	1.00000000
191162	1.00000000
169942	0.98351648
167703	0.18681319
167690	0.18131868
187468	0.18131868
167659	0.17582418
181459	0.11538462
181447	0.10989011
181450	0.10439560
186040	0.09340659
167474	0.08241758

167486	0.07692308
167488	0.07142857
185065	0.07142857
167701	0.06593407
181471	0.05494505
167699	0.03846154
181481	0.03846154

The global reliability index equal to 0.99 confirms the very high level of reliability of the network.

Table 23: Pipes classified according to the HCI (Ugla Network)

Rank	*Relnet*	*Aquarel*	F-Reliab
1	12899	167703	167703
2	184539	187468	167690
3	191162	167690	167659
4	169942	167659	187468
5	167703	181459	181459
6	167690	181447	181447
7	187468	181450	181450
8	167659	186040	186040
9	181459	167474	167474
10	181447	167486	167486
11	181450	167488	185068
12	186040	185068	167488
13	167474	167701	167701
14	167486	181471	1000003
15	167488	167699	181471

5.2.2.2. Crissier

- Failnet-Reliab

Results coming from Failnet-Reliab about Crissier network are presented in the Figure 37, Figure 38 and Figure 39.

The Figure 37 and Figure 38 present the computation of Hydraulic Criticality indices. They show that most hydraulically important pipes are:
- the pipes located near the tank,
- the pipes located on branches,
- the pipes located at the beginning of the main loop.

The comparison between the two figures doesn't show a big difference concerning the hydraulic importance, in spite of considering specific failure probability for each pipe. However some pipes appear as important, regarding the HCI, when specific failures risk is considered.

Figure 39 presents the more vulnerable nodes according to the calculation performed with Failnet-Reliab.

Figure 37 : Failnet-Reliab results on Crissier zone, same failure rate for all the pipes (thickness and darkness of the pipe define its importance)

Figure 38 : Failnet-Reliab results on Crissier zone considering specific failure rates by pipe (thickness and darkness of the pipe defines its importance)

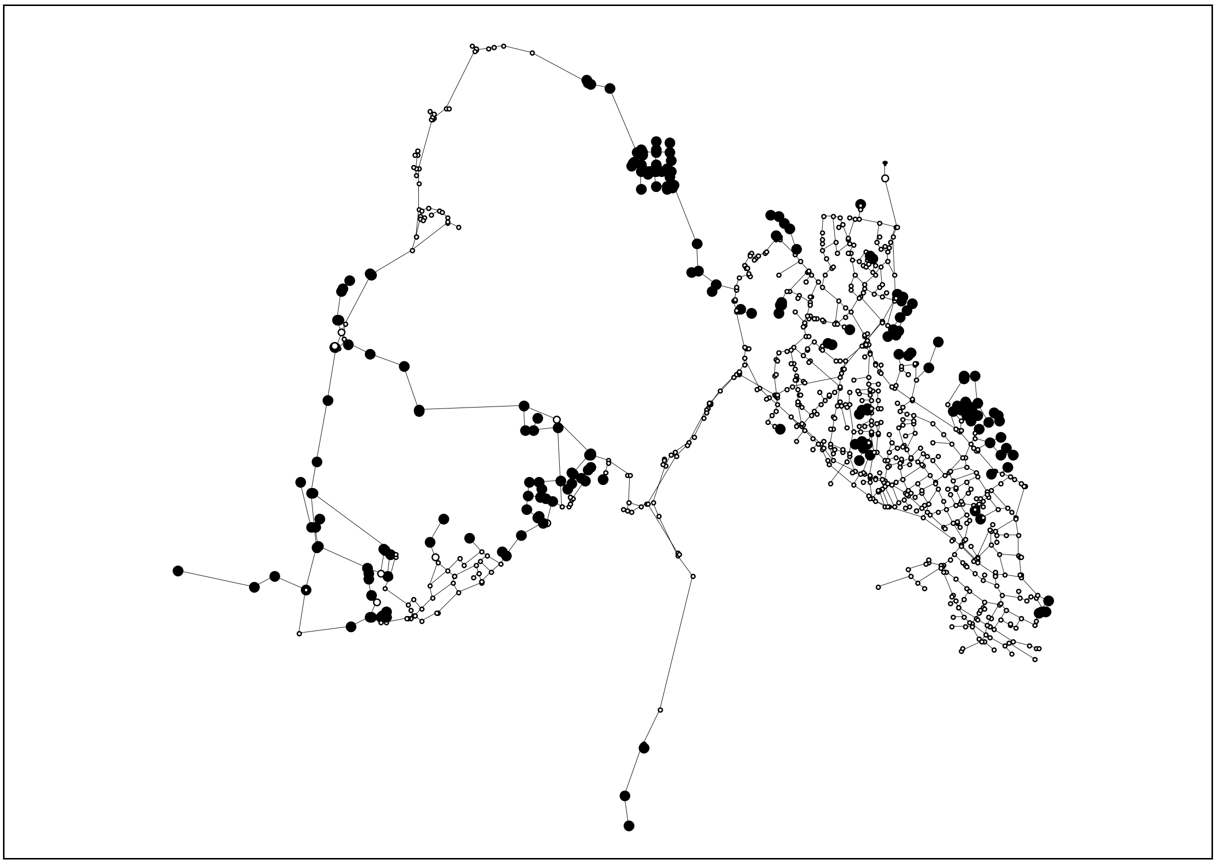

Figure 39 : Failnet-Reliab results on Crissier zone considering specific failure rates by pipe (thickness and darkness of the nodes defines their vulnerability to the failures)

- Relnet

For Crissier the results provided by Relnet are the number of nodes with a pressure below than the required pressure (25 m) and the index giving the impact of the failure of a pipe on the pressure in the node.

The Table 24 gives the 20 worst pipes in the sense of Relnet index.

If we compare with Failnet-Reliab results, we can see 8 pipes are considered commonly in the 20 worst pipes. The main difference is due to considering the length of the pipes to calculate their unavailability.

Table 24 : Classification of the 20 worst pipes according to Relnet and Failnet-Reliab

LinkID	Relnet Classification Removed Nodes	Nodes<RP	Ph14b	*F-Reliab classification*
632	994	0	0	*972*
972	993	1	0	*631*
1075	0	994	0	*632*
631	0	993	0.001	*897*
1063	0	992	0.002	*407*
897	0	991	0.003	*529*
896	0	990	0.004	*432*
1035	0	247	0.7515	*147*
669	0	246	0.7525	*669*
670	0	241	0.7575	*670*
673	0	239	0.7596	*777*
672	0	235	0.7636	*673*
914	0	163	0.836	*672*
1086	0	163	0.836	*776*
630	0	161	0.838	*738*
636	0	155	0.8441	*914*
913	0	152	0.8471	*381*
768	0	150	0.8491	*305*
912	0	144	0.8551	*774*
911	0	140	0.8592	*812*

5.2.3. Conclusion

The tests have shown several approaches concerning the calculation of Hydraulic Criticality indices.

Aquarel allows the consideration of tanks and their emptying to calculate the indices. Moreover it allows to calculates indices according to 2 ways :

- with constant consumption at each node, in this case the indices will be based on node pressure,
- with "sprinkler" : in this case the indices are based on the ratio between consumption and water demand.

Failnet-Reliab, which computes a consumption dependent of the head, gives results close Aquarel with "sprinkler". Moreover considering at the same time the ratio between available consumption and demand and the failure forecast coming from FAIL tools, it allows to highlight pipes and to differentiate them in a specific way.

Relnet allows a simple calculation of indices based on the increasing of pressure, without considering the failure risks. However it provides also results close to Aquarel with constant consumption.

6. GENERAL CONCLUSION

For FAIL Tools (Failure Forecast Models), one objective was to assess the benefit brought by the use of the models by the way of several indices. Another one was to assess the interest of using specific variables, as environmental ones, and to define the minimum data record period to obtain suitable results. As presented in 5.1.3, the tests have shown that a non negligible number of failures could be avoided following the classification of pipes according to failure rates computed with Care-W_PHM and Care-W_Poisson. Moreover it has been shown that very short failure record period (2-3 years) can give suitable results. Only one test allowed defining the interest of considering environmental data (the soil in Trondheim). In this case, considering soil data generated a little benefit, maybe not obvious for Annual Rehabilitation Program, but that could be useful for long term prediction.

More generally, Care-W_Poisson and Care-W_PHM allows the calculable assessment of influence of the different variables on failure occurrence, influence that could have been previously assumed by water utilities. This provides to the service a crucial knowledge of the network and its failure risks.

The tests have also shown the data that were indispensable to be recorded: diameter, length, material and pipe installation date are really essential to make a suitable forecast. Previous studies have been indeed confirmed, i.e. the influence of this variables is very close, by comparing the models as by comparing the networks.

For REL tools, the tests have shown that this kind of tools can really provide interesting criteria, useful for Annual Rehabilitation Program, on condition having beforehand calibrated an hydraulic model. The introduction of forecasted failure rates for computing the Hydraulic Criticality Index can also provide a synthetic result, useful for water utilities. On the long term, applying failure rate forecasted on, for instance, 10 or 15 years, could give evaluate the hydraulic reliability of the network, comparing the present and future global hydraulic reliability indices.

Finally these technical tools provide relevant technical indicators useful to aid decision in of water pipes rehabilitation. Consequently this will allow to base rehabilitation program not only on the failure rate, as it is commonly made, but also on its consequences in term of hydraulic, as in term of cost for water utilities or of impact on customers.

REFERENCES

EISENBEIS, P., LE GAT, Y., LAFFRÉCHINE, K., LE GAUFFRE, P., KÖNIG, A., ROSTUM, J., TUHOVCAK, L., VALKOVIC, P., CARE-W: WP2 – Description and validation of Technical tools D3 – Report on models description. *CARE-W, EU project under the 5th Framework Programme, contract n°EVK1-CT-2000-00053. Cestas (F): Cemagref,* August 2002.

LE GAUFFRE, P., LAFFRÉCHINE, K., BAUR, R., DI FEDERICO, V., EISENBEIS, P., KØNIG, A., KOWALSKI, M, SÆGROV, S.,TORTEROTOT, J.P., TUHOVCAK, L., WEREY, C., Criteria for the prioritisation of rehabilitation projects. D6 report. *CARE-W (Computer Aided Rehabilitation of Water networks), EU project under the 5th Framework Program, contract n°EVK1-CT-2000-00053,* June 2002.

FIGURES LIST

TABLES LIST

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
INSA, Lyon, France
LNEC, Lisbon, Portugal
WRc, Swindon, UK
University of Bologna, Bologna, Italy
University of Ferrara, Ferrara, Italy
AGAC, Reggio Emilia, Italy

Institute name: *Cemagref*
Contact person: Patrick Eisenbeis
E-mail: carew@bordeaux.cemagref.fr
www.cemagref.fr/English/more-infos/water-waste.htm

Address: 50, avenue de Verdun
33612 CESTAS Cedex, France
Phone: (+33) 557 89 08 00
Fax: (+33) 557 89 08 01
Work Package: 2 Task no.: 2.2