UTILNETS: A Water Mains Rehabilitation Decision Support System

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Abstract

UtilNets is a decision-support system for rehabilitation planning and optimisation of the maintenance of underground pipe networks of water utilities. The DSS performs reliability-based life predictions of the pipes and determines the consequences of maintenance and neglect over time in order to optimise rehabilitation policy.

Keywords: water network maintenance, rehabilitation planning, probabilistic model, decision support system, geographical information system

Introduction

Many cities are now faced with the major task of rehabilitating their water mains.

Twenty percent of these mains in large metropolitan areas are below central business districts and if they fail this will result in severe traffic disruptions. Critical in the event of failure are also pipes whose collapse would result in unavailability of potable water to hospitals and other important customers, unavailability of water for fire fighting, contamination of the water supply and considerable third party damage from flooding. UtilNets is a prototype decision-support system (DSS) that performs reliability based life predictions of water pipes that can be used for the pro-active rehabilitation of critical water mains.

Additionally, UTILNETS, that also determines the consequences of pipe maintenance and neglect over time, can be used to optimize pipe rehabilitation policy and determine the required rehabilitation budget of water utilities.

The UtilNets prototype is the result of 3 years research and development funded by the European Union. It was developed by a consortium of structural and reliability engineers, computer scientists specializing in geographical information systems, relational databases and expert systems, all assisted by a large water utility.

The prototype of UtilNets has been implemented for grey cast-iron water pipes, but is extendable to other pipe materials, and includes the following:

- Probabilistic models that give a measurement of the likelihood of structural, hydraulic, water quality and service failure of pipe segments over the next several years.
- Assessment of both the quantifiable and qualitative consequences of various rehabilitation options and neglect over time.
- Selection of the optimal rehabilitation policy for each failed pipe segment.
- An aggregate structural, hydraulic, water quality and service profile of the network together with an assessment of the required rehabilitation expenditures.
- An assessment of network reliability in terms of demand point connectivity and flow adequacy.

Since most utilities have in general incomplete information about the state of the pipe network, a complex Default Manager has been incorporated to yield reliable forecasts even where data is incomplete. Probability curves are provided to assist the Default Manager where applicable.

Overview of Existing Approaches

The major objectives when applying rehabilitation methods for water networks are

- to maintain the hydraulic capacity

- to avoid future water quality problems
- to avoid future bursts and leaks

The most common method of on-line and continuous operation monitoring is by registration of water flow or the pressure through strategic pipes within the network. If the flow or the pressure for some reason changes, this might be a sign of an operational failure, which can be a burst or a leak. Many cities have separated the network into “leakage districts”, and have installed water flow and pressure meters to monitor each district. The registered data are checked and necessary actions taken. Data on bursts and leaks are collected and evaluated to estimate the future need of rehabilitation.

In spite of several good arguments for pro-active maintenance, still, in general, the rehabilitation of water networks is based on repairs after failures have occurred. This method is called the “re-active” maintenance, the “ambulance method”, etc. It is a fact, though, that it will be less expensive not to intervene in spite of a high failure rate, if not indirect costs and other inconveniences of water shortage and repair actions are included in the decision criteria.

In the last years, several municipalities have started to use a “cluster theory”, which says that a major part of the pipe failures will occur within a short distance from previous failures (Sundahl, 1996). When several failures have occurred within a limited area, this may give a strong argument for rehabilitation actions.

During the last 10 – 20 years, several cities have started to use computer based water network records. These databases contain information on network properties, such as pipe material, construction year and diameter, and failure information (where, when, failure description, etc.). By simple analyses of these data or by employing more complex statistical methods, information is collected to show differences in failure rate for different pipe properties.

The expected pattern of a single pipe failure is a critical factor for reliability analyses. The future resistance of a pipe against failure can be estimated by deterministic and probabilistic methods. There are a number of methods, which are currently being used in various research projects. These methods can be classified in four groups:

- *Structural failure time modeling* of cast iron and ductile iron pipes. This method is based on the calculation of external mechanical loads and measurement of corrosion on pipe samples. The variation of corrosion and the variation of external load can be described with a probabilistic model.
- *Counting processes and extrapolation techniques.* These methods are based on the number of recorded breaks and leaks within a period of operation. Accumulated figures of failure frequencies for single pipes (or groups of pipes of different properties), show the failure frequency tendency. An increasing failure rate motivates for an increased rehabilitation rate. Future failure frequencies can be estimated by extrapolating the trends obtained from historical data.

- *Failure development processes*. Using a stochastic "survival" model, the expected number of failures during a given time period is computed. These survival functions are based on the same data as the counting process, and represent a method based on time until a failure may occur.
- *Network survival modeling based on expert judgement.* The survival of pipes within a network is modeled with aging functions derived from expert estimates on the service life of categories of pipes. While the service life of a pipe is treated as a random variable with specific density distributions, there is no formal relation to its previous failure or leakage rate.

The principles of analyzing and forecasting models, and systems for water records are quite established (Di Federico, Mazzacane & Schiatti, M, 1998; Herz, 1996; Herz, 1998; Prost, Miramond & Le Gauffre, 1998; Le Gauffre, 1997; Malandain, Le Gauffre & Miramond, 1998; Lei & Saegrov, 1998; Røstum, Dören & Schilling, 1997; Røstum, Baur, Saegrov, Hörold & Schilling, 1999; Saegrov, 1999). However, so far these tools have only been applied to a very limited extent, and the need for a complete system for supporting decisions on rehabilitation needs, including cost data, has not been addressed yet (Conroy, 1996).

Overview of the UtilNets Approach

The classic survival function for a group of water mains is shown in Figure 1. The early part of the curve shows “infantile failure” which for pipes is representative of failure due to human factors in the actual laying of the pipe (manufacturing faults, tend to appear during that part). A period of time follows in which failure rate, *F1*, is generally low. When failure does occur it may depend on a wealth of factors, such as excessive loads not designed for, or settlement. As the pipes tend towards the end of their useful life the failure rate increases exponentially. This classic survival profile is known as the “Bath Tub” curve. The “Bath Tub” curve can be applied to an individual pipe, a group of pipes with similar characteristics or the whole population of a pipe network.

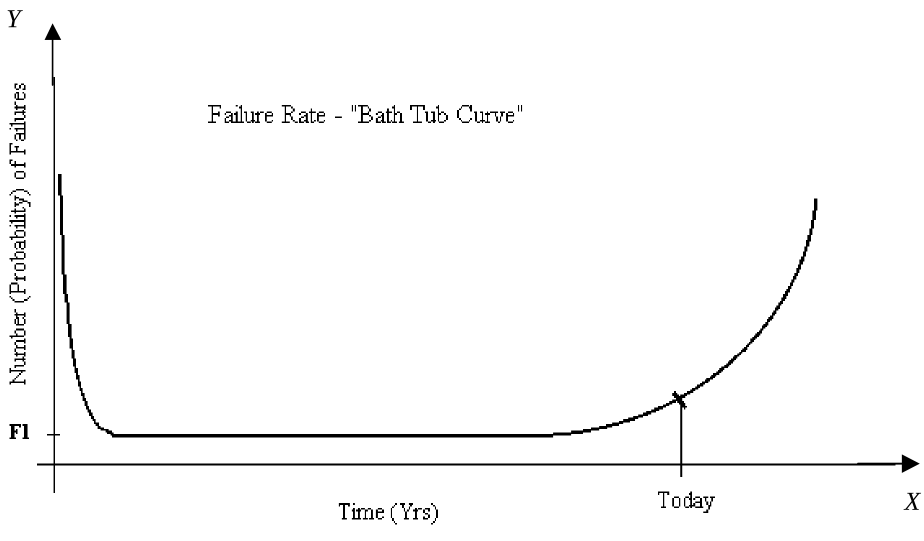

Figure 1: The Bath Tub curve.

An understanding of the underlying principle of the "Bath Tub" curve (and its deficiencies) is central to realizing the potential of UtilNets. With respect to Figure 1, assume that the failure rate is predicted to increase above and beyond the *F1* level. This increase may have started already or will take place in the near to medium future. Analysis of historical data does not allow us to identify the *F1* level of mains failure unless we have all the data going back to when the pipes were laid. Many cast iron pipes have been in useful service for well over 100 years but the degradation process has already started. Analysis of burst data over just the last 10 years may not be really significant in relation to the whole life of the network. When mains have been added to the network throughout its life, and some of the older ones have been already rehabilitated, the analysis becomes more complex.

A graphical representation of the complexity of the problem is shown in Figure 2. Consider a typical "Bath Tub" curve for a population of Cast Iron pipes that were all laid about the same time over 100 years ago, in similar ground conditions, with similar loads being applied. The length of mains requiring replacement can be interpreted from the secondary *Y*-Axis (*Y′*).

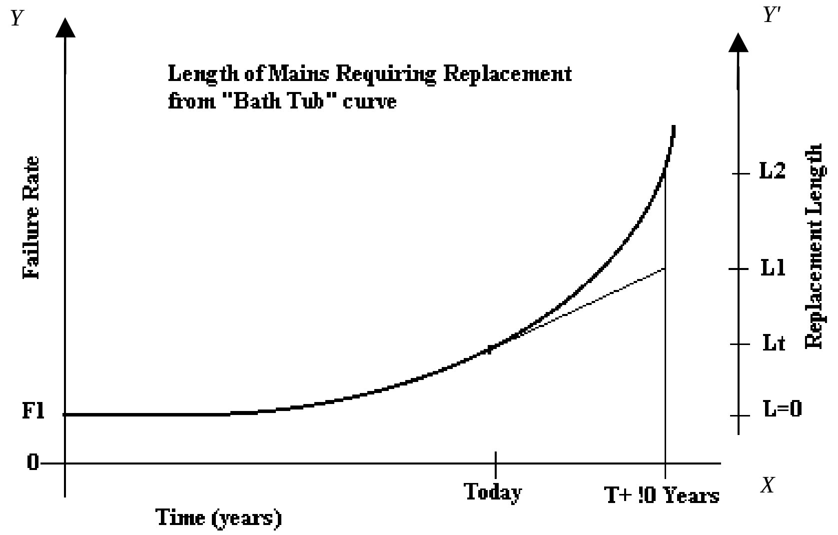

Figure 2: Tail End of the Bath Tub Curve.

Since the lower levels of failure rate during the static period of the curve, i.e. at *F1*, would be related to non-time dependant failure and would therefore be repaired pipes, which would not be expected to fail again, then this could be related *to L=0*. *L=0* represents nil length of pipe requiring replacement or rehabilitation.

From an assessment of data available from recent years, including metallurgical data from selected pipe samples, individual pipe burst data and overall burst rates could be assessed. Engineers could then draw conclusions on the length of pipes that would need to be replaced to maintain current levels of serviceability. This would be represented by L_t.

Using both historical data and statistical analysis a length of pipe needed to be replaced in the next, say, 10 years could be derived and this would relate to *L1*. The level of confidence in this method would be rather low.

The above techniques require an undertaking of vast amounts of pipe sampling or condition assessments and measurement of long lengths of pipes, all at enormous cost and with questionable accuracy.

In contrast to conventional models, which attempt to predict pipeline failure based on service failure statistics and using data from specific systems, **UtilNets is based on physical models of the degradation process**. Such models employ engineering based equations to derive structurally based estimates of pipe conditions. The decision support system optimizes the individual rehabilitation policy for each segment and the ranking of rehabilitation within the whole network. It provides a forecast on the aggregate structural, hydraulic, water quality and service reliability profile of the network together with an assessment of the required rehabilitation expenditures.

UtilNets determines the prospective life expectancy of pipe segments and supports the prioritisation of rehabilitation measures. Thus, the system offers the possibility to optimise long-term financial and technical planning for the maintenance of the underground network.

While conventional water-network management-systems are restricted to statistical projections of historic burst rates etc., **UtilNets analyses all important environmental influences** and load effects that have affected or will affect the pipe during its whole lifetime.

UtilNets will answer questions such as:

- What is the structural life expectancy of a specific water main segment?
- What is the probability that the pressure at the end of a specific water main segment will be adequate in 3 years?
- Which pipe segments will cause dirty water problems?
- What is the optimal rehabilitation scheme for a specific water main segment?
- What should be the current rehabilitation budget for the utility?
- What should the future rehabilitation budget for the utility be in 5 or 10 year’s time?

Turning to Figure 2, an expert engineer could predict the future failure rates, if equipped with a proper understanding of the degradation processes of pipes, data on the likely loads that might be applied, and a full assessment of historic data. From this, s(he) would determine the length of pipe, *L2*, that would need to be replaced to provide the current levels of service in the 10-year time horizon as given above. A failure to understand this process is likely to result in excessive amounts of replacement and maintenance work instead of spreading the work-load leading up to this time.

Of course, the actual time-scales involved will depend on the type and frequency of loads being applied, the rates and types of internal and or external deterioration, etc. However, the comparison above is fundamental to highlight the mentality shift from the classic approaches to UtilNets.

An example of using UtilNets

This section briefly sets out an example on how UtilNets can be used.

A city has to repave the main road in the business district. The water utility in the area needs to know if this is a good opportunity to replace the water main below this road. This is a cast iron pipe that was built in 1945. Its original internal diameter was 500 mm and its original wall thickness was 18 mm. It is exposed to a surge pressure of 758000 N/m^2 five times a year and a continuously applied working pressure of 448000 N/m^2. It is buried 2 meters below the surface of a highly used road and is exposed to differences in temperature of 15° C. Furthermore, because of water leakage that caused soil erosion below the pipe, 1.5 m of the length the of the pipe is unsupported. Additionally, this pipe is subjected to internal and external corrosion that can be expressed as $a(t)=d \cdot t^b$, where: $a(t)$ is the maximum depth of corrosion in mm, t is exposure time in years and b and d are corrosion coefficients. The latter for external corrosion take the values of 0.4128 and 0.427107 for d and b respective while for internal corrosion they take the values of 0.9253 and 0.3776 for d and b respectively.

Based on the above inputs UtilNets produced the plot in Figure 3 that shows that by the year 2001 the probability of failure of this water main will be very high. Accordingly, it is in the utility's best interest to replace the pipe now. Note that the plot is taken from an actual screen shot of the UtilNets software: axis *X* corresponds to time and axis *Y* corresponds to probability of failure.

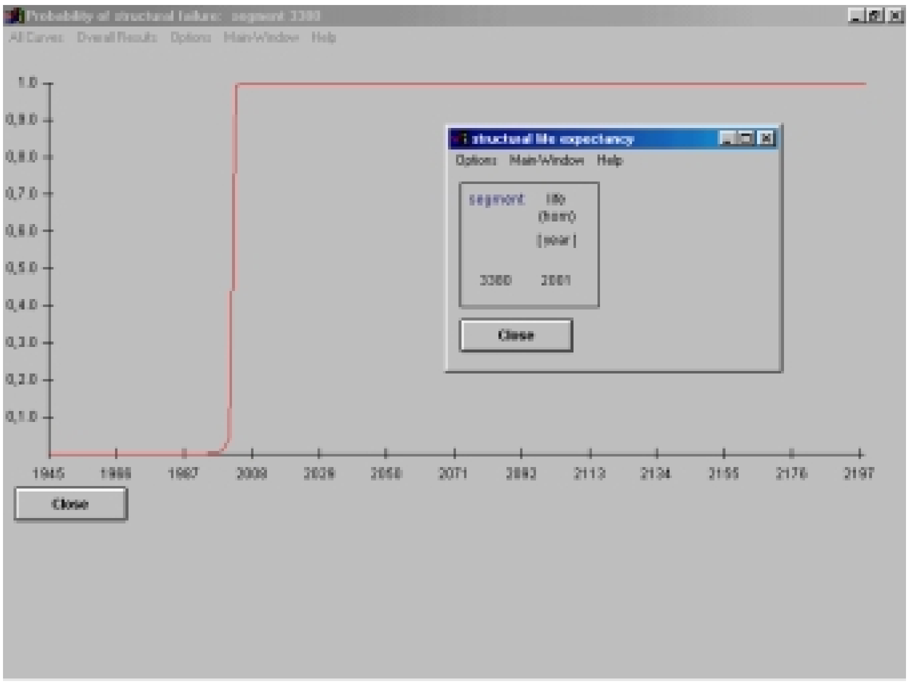

Figure 3: Probability of Structural Failure of a Specific Water Main as a Function of Time.

Features of UtilNets

UtilNets performs the analysis of pipes by means of several Modules. These Modules can be divided into three groups:

Analysis:

- Structural analysis
- Hydraulic analysis
- Water quality
- Service reliability

Optimization:

- Options and capital costs for water main rehabilitation
- Non-quantifiable consequences of failure (“Risk Module“)
- Prioritization of water main rehabilitation

Background Information:

- Network reliability

The basic entities analyzed by UtilNets are links and segments. Both are part of the length of a water pipe:

A **link** is the length of pipe between two nodes. A node may be a connection of pipes, a network building such as a reservoir or just a change of basic characteristics, e.g. pipe material or age.

A **segment** is a part of a link. Links may be divided into segments for various reasons, e.g. if a main road crosses the link, the part under the road is considered a separate segment. A long pipe can be divided into segments of equal length.

Structural Reliability Module (M1)

For each selected pipe segment, the structural performance in service is assessed in this module over time. First, the progress of deterioration caused by corrosion is determined. The resulting decrease of resistance is compared to the internal water pressure and external loads (soil, temperature, traffic etc.). By defining the operating characteristics of the water main (pit depth, stress and stress intensity factors), the operating limit (wall thickness, strength and fracture toughness) and their respective probability distributions, an estimate of structural reliability is obtained by monitoring as a function of time, the magnitude of the interference between these two distributions. When the operating characteristics reach a prescribed limit the pipe, link, segment or whole network begins to operate unsatisfactorily and this qualifies as failure.

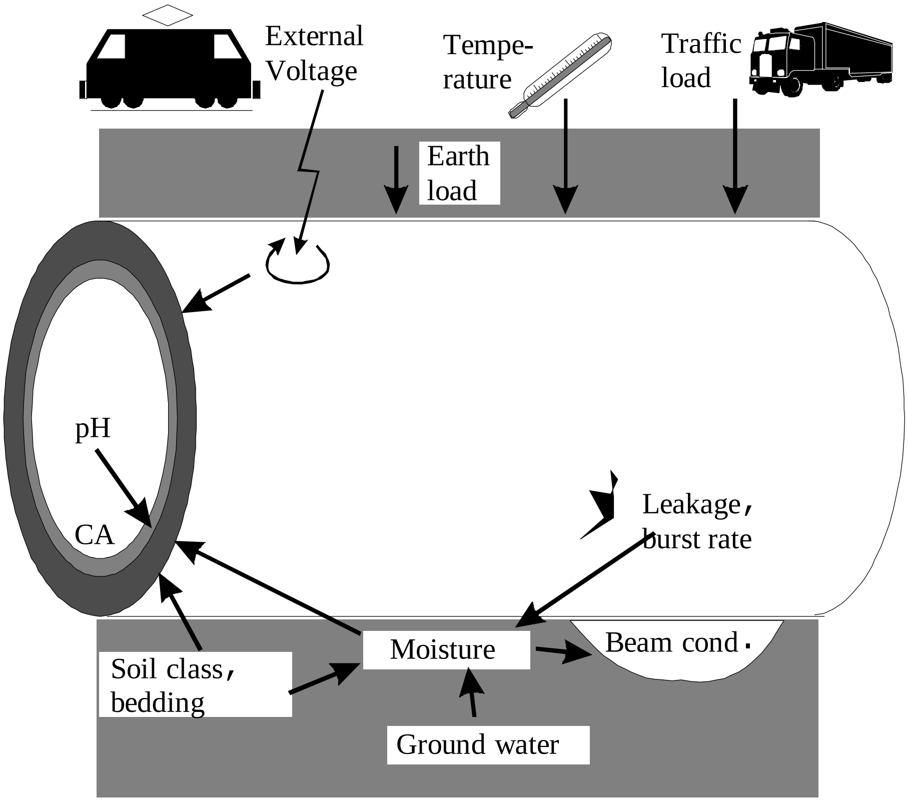

Figure 4: Loads that may be applied to a pipe.

The loads applied to the pipe that have been considered are shown in Figure 4.

Structural analysis is performed in two steps, deterministic and then stochastic:

The deterministic approach calculates all the constant or frequently applied loads, summates them according to the direction in which they operate and compares them with remaining stress and strain carrying capacity of the pipe. This can be compared to the conventional process of designing a pipe from a list of known and given loading conditions.

There are deterministic sub-modules:

- Loads: compute present values for loads and stresses.
- Safety Factors: based on the loads and stresses, a first estimate is given for each selected segment. For several features such as internal pressure, a ratio between the strength of the pipe segment and the loads is given as a safety factor. The user might focus, for instance, on the “worst” segments for the next steps.

Due to the degradation of the pipe there is a point in time where the probability of different loads being applied together at the same moment will cause the pipe to fail. From this point on the system considers the probability and randomness of these loads, their type and frequency, and the future degradation of the pipe. The pipe degradation previously computed is compared with a stochastic process of load events (e.g. meeting of heavy trucks above a pipe segment, in cold weather).

There are, also, stochastic sub-modules:

- Structural Reliability: compute the structural life expectancy for each selected segment, by estimating the probability of coincidences of external loads.
- Structural Reliability fast: Here, only the first year where risk for the pipe rises above zero is computed. (In contrast, the full version computes a curve showing the increasing risk from zero to one over time.) If only aggregated data is needed for the priority of rehabilitation, this fast version is recommended.

Hydraulic Reliability Module (M2)

The hydraulic performance of a water main in service is assessed by comparing its state of behaviour, as a function of time, to each one of two limit states. These limit states are defined as:

- The maximum demand requested, and
- A specified minimum operating pressure.

The method is similar to the one adopted for the structural sub-module and is based essentially on the analysis of interference data. An estimate of hydraulic reliability is obtained by monitoring, as a function of time, the magnitude of the interference between the operating characteristics on the water main (friction factor, head loss, etc.) and the operating limits (max. flow and min. pressure)

Water Quality Reliability Module (M3)

This module takes into account effects that pipe condition can exert on water quality, i.e. the inside surface of the pipe can corrode and the corrosion products can pass into the water. The module is built around pre-existing research available in the literature on the interaction between pipe materials and water quality parameters.

Service Reliability Module (M4)

Service Reliability comprises all the reliability results given above: structural, hydraulic and water quality. It is defined by the combined probability of a segment suffering none of these failures in a given year. This is then calculated into the future until a failure or probability above zero occurs.

Options and Capital Costs for Water Mains Rehabilitation (M5)

For water mains with a structural or hydraulic or water quality failure predicted by one of the above Modules, a list of technically feasible rehabilitation solutions is generated. This takes into account technical rules, flow carrying comparisons of the different rehabilitation technique and scheme details that might preclude some remedial measures. For these solutions the net present value of cost is derived in order to select the technically feasible option with the min. cost.

Non-Quantifiable Consequences of Failure ("Risk Module", M6)

A water pipeline failure can deprive sensitive customers of supply or cause collapse of other utilities or produce damage to streets and other structures, or any combination of these. This has to be taken into account in assessing priorities for water mains rehabilitation.

A table has been produced which ranks each consequence both individually and in combination with the others. The ranking is implemented as an ad-hoc scoring scheme, where a large number indicates a grave consequence. A failing link is then assigned a score for each one of the identified risk parameters based on which an overall hazard score is derived. The system is able to select only those consequences that derive from the related cause of failure; e.g. hydraulic failure does not have consequences for damage to other utilities, whereas structural failure will have consequences for both sensitive customers and also damage to streets.

Prioritisation of Water Main Rehabilitation (M7)

Priorities for rehabilitation are assigned, for all failed links, based on hazard potential and rehabilitation cost.

Network Reliability (M8)

In trunk mains the inter-connectivity is limited but in distribution mains the network often has large amounts of redundancy. There is rarely true hydraulic redundancy but there is a measure of inter-connectivity that can be exploited. The UtilNets system has a module to assist engineers to understand the reliability of a supply system without doing numerous iterations on a complete hydraulic model with a complex network solver.

Two reliability measures are assessed:

- Demand point connectivity (that is, the probability of complete isolation of each demand point from a water source point).
- Adequacy of flows at each demand point. Since complete hydraulic calculations and conventional 24-hour simulations are not undertaken within UtilNets a true adequacy of flow can not be provided. An "adequacy of flow" is determined based on rules from which the engineer may select a short list for subsequent analysis in a proprietary hydraulic model.

Decision Support System

A complex DSS such as UtilNets needs a User Interface (UIF) and central control unit, which are flexible and "intelligent" in various aspects. In UtilNets this is achieved by using Expert System (ES) development technology. The ES comprises several layers (see Figure 5):

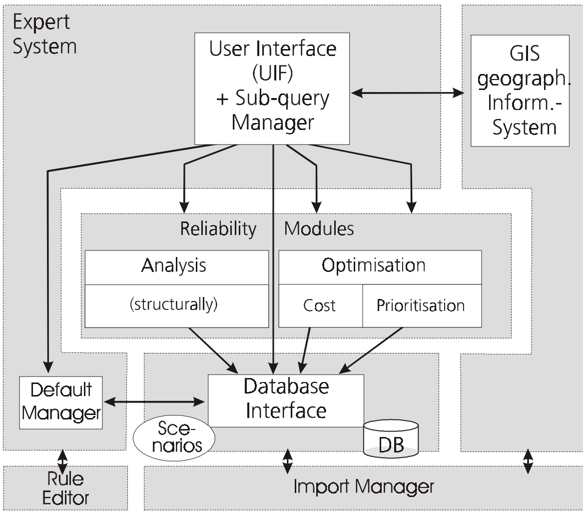

Figure 5: The structure of the Decision Support System.

- A high-level domain model representation allows experts to "feed the system with knowledge" in their own technical language, which is compiled into an efficient internal format. Hence, the ES combines declarative expert knowledge with efficient internal procedural knowledge.
- The adaptable graphical UIF guides the user in a clear, concise and easily understandable manner.
- The Scenario Manager allows experiments, i.e. questions under the assumption of different states in the utility network now or in the future ("What-if" questions).
- Computation-intensive Reliability Modules are coded in conventional C programs. Rule-based Modules are defined in terms of high-level ES rules (see Table 1, for an excerpt of hydraulic rehabilitation rules). The Subquery Manager of the ES allows for a flexible combination of both kinds of modules.
- The rule-based Default Manager serves for intelligent data management in case of missing data.

On-line Data Dictionary

A data dictionary has been prepared as part of UtilNets to assist both the utility expert user in setting up the system and users with an engineering background. The data dictionary sets out the way in which data is held, by both type and units. This dictionary is available at all times to assist the users in ensuring that they can comprehend UtilNets's processes and output. The data dictionary is a table, which describes all notions of the underlying Domain Model.

"What If?" Scenarios

Experiments with "What-If" Questions are designed into UtilNets.

As a rule, water utilities do not have complete data either on the pipes or on the budget they can spend in the future. In order to deal with this situation, UtilNets allows for two approaches.

First, the Default Manager provides estimated values in the absence of input data. It is based on default rules (i.e. rules of thumb from context information), although currently default rules cannot be changed during runtime.

Secondly the user can change database values. Such a change is called an “experiment“. By changing one or more values, the user puts a question to the system:

“**What** happens to the results of the analyses **if** I change this feature to that value?”

Such kind of experiment with “What-If” questions are useful, e.g. If the database contains no or only guessed data, then the user can “play” with other possible data ranges. For instance: “What is the structural life expectancy of these segments if I decrease their year-laid by 20 years?”

The user can see the result of “What If” operations and compare them with other experiments. Again, the user can “play” with alternatives. For instance: “What is the impact on serviceability of these demand points if I replace that link now or in 10 years?”

Geographical Information System

The UtilNets system stores the actual geographic location for all parts of the underground network (pipes, valves, etc.) in a Geographic Information System (GIS). Thus, it can correlate the water network:

- With soil types and temperature data (in order to better estimate corrosion rate);
- With existing ground structures, such as roads, (in order to calculate extra loads on pipes);
- With consumers, such as hospitals (in order to estimate consequences of failure), etc.

The fully fledged GIS incorporated in UtilNets also provides a powerful user interface which allows the engineer using the system to selectively examine parts of the network based on their location with reference to streets, cities or other landmarks.

UtilNets as a Case Study in Urban Knowledge Engineering

Rehabilitation of deteriorating underground water mains is an environmentally sensitive issue; it is bound to become even more so, given the fact that water is increasingly a scarce recourse.

The reliability of a water network is a taxing exercise in spatial modelling. UtilNets has demonstrated that an overall reliability index may be also elusive to formulate if adequate knowledge about the network is not present. Entities such as pipes have to be physically modelled to assess their structural integrity; then spatial relations are processed to infer hydraulic or overall network capability; then such capability is also related to spatially dispersed customers to estimate the cost of failure. As if the above setting was not enough of a problem, time comes into play as well, resulting in a fluctuating overall network capability and a constant need for monitoring.

UltiNets provides forecasts of failures in long time horizons as well as a recommendation of prioritizing the rehabilitation of water mains. This latter fact makes UtilNets a very powerful tool for long term planning as it allows water utilities to forecast and budget for maintenance requirements, in selected target areas. It is a tool for pro-active rather than re-active management.

The work in UtilNets has uncovered a wealth of information available at water utilities. However, this wealth exists in a truly distributed format: from heterogeneous computing environments, to paper records, to hearsay. A major issue in the current phase of work on the UtilNets system is the development of a data fusion environment to allow the practical gathering, validation and cleaning of data that must be fed to UtilNets. To ensure that this environment can be seamlessly integrated into the working practice of various utilities (UtilNets **is** slated to appear as a product), a very detailed data model has been refined to reflect a thorough, content-oriented, breakdown of the water network (in terms of objects, their properties, etc). Perhaps not surprisingly, the existence of this domain model that facilitates the take-up of UtilNets is an exemplary demonstration of knowledge reuse practice, as currently prominent in the research field of ontologies (Chandrasekaran, Josephson & Benjamins, 1999). Though an ontology has not beet formally constructed during UtilNets, an intuitive breakdown of notions and their subsequent modeling into the domain model and the database design can be roughly described as an initial approximation to a developing ontology (see Figure 6). This experience during UtilNets has also uncovered that the data dictionary should only serve as a text-only repository of terms whereas the interrelationships between notions can be best captured in a schematic way.

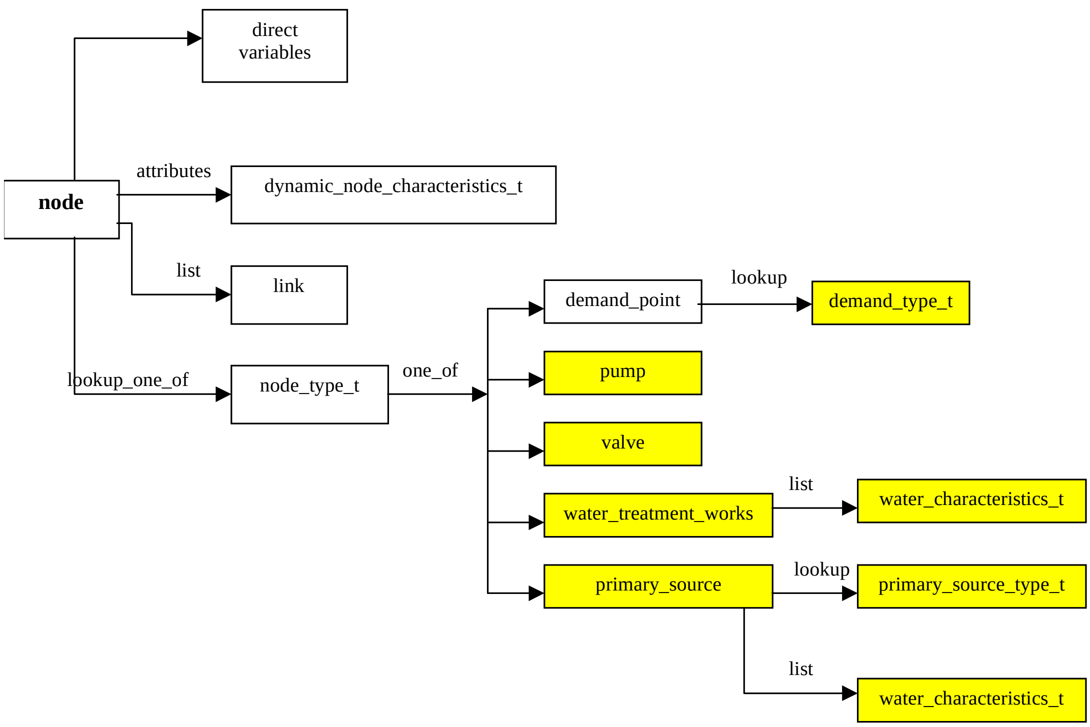

Figure 6: An excerpt from an ontology approximation on underground water resources.

Conclusions

There were some fundamental findings of this research project. Obviously our understanding of pipeline degradation has been significantly enhanced during the work performed to collect the data that provides the background to UtilNets.

Even though the current version has not yet demonstrated its value to utilities around the world, it can be put to use to at least steer water engineers to locations of up-coming problems.

A significant by-product, however, is also the understanding that collecting the vast amount of data required to populate the databases will be resource intensive unless utilities start to collect similar data during their normal operations, realizing their potential use to future maintenance problems.

UtilNets in its current prototype form is too rigid, too complex and may require amounts of data that may be unaffordable to collect and to enter to the system. For this reason more utilities are being involved from across Europe to help the developers in designing the commercially available version of UtilNets.

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UtilNets has been a case-study project in inter-disciplinary work. Since 1993, when the original idea was coined, dozens of people have provided input to UtilNets (and a lot of them still are), working for the organizations of the consortium. It is not possible to list all of them here, but special credits are due to Anna Stathaki, Yannis Theodoridis, Nikolina Renieri, Kriton Kyrimis, George Tsironis, Antonis Chatzoulis, George Pampoukis, Corrado Sana, Martin Beyer, Afshin Zadeh–Khorassani, Peter Mahon and Axel Koenig.

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Vitae

Dr Thanasis Hadzilacos, 46, is a senior researcher at the Computer Technology Institute of the University of Patras, Greece, and the research director of R&D Unit III "Applied Information Systems". He was the scientific coordinator of the UtilNets project in which the system was originally designed and developed. He specializes in large-scale information and database systems and in particular database design for non standard application areas such as GIS, education and multimedia. Educated at Harvard University in the US, he had a long industrial experience before joining CTI in 1986. He has published over 30 articles on Geographic Application and Database Design, Database and Object Base Transaction Processing, Educational Software Design, and Multimedia Systems.

Dr Dimitrios Kalles (born 1969) received a diploma in Computer Engineering and Informatics at the University of Patras (1991) and an M.Sc. (1993) and a Ph.D. (1995) in Computation from UMIST (Manchester). He joined the Computer Technology Institute in 1997 and now works as a researcher supervising applied research projects and the basic research prototypes on machine learning and geographical information systems. He has co-authored at least 10 international publications.

Nick Preston (B.Sc., C.Eng., MICE) has worked in the water industry for over 15 years with specific experience and interest in holistic and global engineering of water and sewerage pipelines. Past involvement in planning, design, specification and construction of pipelines has introduced him to the wider field of operational optimization and whole life cost management of large pipe networks. The key purpose of these networks is to supply levels of service to the end customers to which they are connected. Recent research undertaken by Nick, for North West Water, on pipeline materials and network reliability for optimum customer service has shown that urban collections of customers need special engineering skills to be applied to maintain and operate their water service systems.

Paul Melbourne (B.Sc. Chem) has worked in various roles within the leading edge of the scientific community serving several Water Companies. There has historically been a critical role for water scientists in the water industry to ensure that the water customers receive, to drink or not, and the quality of waste water effluents discharged to the environment are of the highest quality. Recent EU regulations on water and waste water effluents have ensured there is a continuing need to develop novel technology and management techniques to increase quality whilst reducing whole life costs and customer bills. Paul has been developing systems to monitor and control the physical whole life water cycle at lower whole life costs, including work on knowledge engineering and understanding social cost.

Prof. Leonidas Camarinopoulos (born 1946) received the Degree (1970) in Electrical Engineering and PhD (1974) in Reliability Theory from the Technical University of Berlin. He was research scientist at the Nuclear Research Center in Athens, a research Fellow at the Nuclear Research Center at Juelich, a Professor of Risk Analysis and Nuclear Safety at the Technical University of Berlin and a Professor of Applied Statistics and Risk Analysis at the University of Thessaloniki. He is currently a

Professor of Risk Analysis and Reliability Theory at the University of Piraeus, President of the Greek Atomic Energy Committee and Director of RISA Ltd. in Berlin. He has published over 100 articles in system reliability, risk analysis, nuclear safety, discrete structures, probability theory and statistics.

Dr Michael Eimermacher (born 1955) is a Dr.-Ing in Computer Science (Technical University Berlin). He has been involved in several projects, amongst which are the design of application packets and extensions for the multi-media teleservice platform and intelligent agent based services of the German Telekom, the EC project consortium UtilNets (BRITE, Innovation) for knowledge-based optimization of maintenance efforts in wide spread utility networks, the design of a rule based approach for semi-automatic R/3 configuration for SAP AG and the design of AOT (agent oriented technology) for eCommerce (1:1 marketing), supply chain management, etc.

Vassilis Kallidromitis (born 1944) received a Degree in Civil Engineering -Section Transport- from University of Rome “La Sapienza”. He is a member of the Board of Directors and the Director of Structural and Hydraulic Division of TECNIC Consulting Engineers S.p.A.

Dr S. Frondistou-Yannas studied at the Massachusetts Institute of Technology where she obtained an M.S. and a Ph.D. in Civil Engineering and an M.S. in Management. Subsequently she became Assistant Professor of Civil Engineering at MIT where she conducted research on materials and project management. During the lent 15 years she is the President of SEPTE Ltd in Greece and is involved in research on construction maintenance and rehabilitation.

Dr Sveinung Saegrov (born 1951) received a Dr.ing in Civil Engineering at the Norwegian University of Science and Technology 1992. He is a senior research engineer at SINTEF Civil and Environmental Engineering, in the department of water and waste-water. His main field of competence is water and sewer network management. He has coordinated the "State of the art report on Urban Runoff in Cold Climates" (1999) UNESCO report and has lead the working group on "Structural and functional deterioration of water pipes" under COST C3 mission. He has served as external examiner to doctoral theses and has over twenty international publications.

Figure legends

Tables

If A?B	If	If	If	If	Then
<=	Nominal diameter <= 200				**6**
<=	Nominal diameter > 200	Nominal diameter < 400			**7**
<=	Nominal diameter >= 400				**8**
>	Working pressure >= 1600000				**4**
>	Working pressure < 1600000	Nominal diameter <= 100			**1**
>	Working pressure < 1600000	Nominal diameter > 100	Nominal diameter <= 250		**2**
>	Working pressure < 1600000	Nominal diameter > 100	Nominal diameter <= 250	Nominal diameter >= (215,9 - 1,905 x Normal CA Level)	**1**
>	Working pressure < 1600000	Nominal diameter > 250		Nominal diameter < (215,9 - 1,905 x Normal CA Level)	**3**

Table 1: An excerpt from a list of UtilNets's hydraulic rehabilitation rules. *A* stands for *average_leakage* x *length* / 3600. *B* stands for 0,3 x *average_flow*. Column *Then* cites the index number of a particular rehabilitation method.