SIROCO, a decision support system for rehabilitation adapted for small and medium size water distribution companies

E. Renaud[1], JC. De Massiac[2], B. Brémond[3] & C. Laplaud[4]

[1] Cemagref, 50 avenue de Verdun 33612 CESTAS France, eddy.renaud@cemagref.fr

[2] G2C Environnement, 13770 VENELLES France, jc.demassiac@g2c.fr

[3] Cemagref, 50 avenue de Verdun 33612 CESTAS France, bernard.bremond@cemagref.fr

[4] G2C Environnement, 13770 VENELLES France, c.laplaud@g2c.fr

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Abstract

The SIROCO project (Système Intégré d'aide au Renouvellement Optimisé des COnduites adapté aux petites et moyennes collectivités distributrices d'eau potable) financed by the French Ministry of Research, is the result of a collaboration between Cemagref and G2C Environnement.

In the framework of the European Commission-funded project, Care-W, (Computer Aided Rehabilitation of Water Networks) several tools and methods were developed, tested and then combined into an integrated decision support system for the rehabilitation of water distribution networks. Generally, Care-W was geared towards larger water companies with sufficient data at their disposal.

The aim of the SIROCO project was to create a tool enabling small and medium size water distribution companies to prioritise pipes for rehabilitation. Individually, these companies do not have enough data to obtain reliable results from break prediction models. In order to overcome this problem, an amalgamated database consisting of data from several companies was proposed. In order to standardise and manage the data more effectively, a geographic information system (GIS) developed by G2C Environnement was used.

A consortium of 16 water companies was established. Data defined in the framework of the project were collected and incorporated into the GIS by means of a purpose-designed interface.

Cemagref then tested the principle of using a break prediction model on an amalgamated database. This enabled the feasibility of such a database to be evaluated. The predictions permitted the subsequent prioritisation of pipe rehabilitation candidates.

Cemagref also tested a hydraulic reliability model on several of the water distribution networks. These tests were able to show that hydraulic reliability software can be used with data originating from a GIS, providing certain topological rules are respected.

A decision support system was constructed, based on specifications and constraints of the various water companies. It was designed to create a hierarchy of potential rehabilitation candidates based on pertinent criteria. The multi-criteria approach considers both the impact of failures and the opportunities for rehabilitation. The selection of criteria results from a compromise between these impacts and opportunities and by using the appropriate tools for the data available.

On the basis of this project, G2C Environnement has developed the "SIROCO" software. An interface has been designed to allow the user to import all the necessary information at the beginning. Tools have also been developed to control the data and take into consideration the original topology of the network. An options module allows appropriate parameters and criteria to be chosen for each user. The mutualisation of the database is performed on a server by Cemagref with import and export functionalities being developed for this effect, so that each individual user only has access to his own data. From the data and model results, a separate module allows the multi-criteria analysis to be performed. This determines the ranking of pipes as rehabilitation candidates – information that can be displayed in graphic form on the GIS.

Introduction

Context

In the context of the European Care-W project (Computer Aided Rehabilitation of Water Networks), tools and methods were designed and tested then combined into an integrated decision support system for the rehabilitation of drinking water distribution networks (Torterotot et al. 2005).

The different tools developed rely on a database in which information relating to interventions on the network plays a central role. The multicriteria tools used for the annual programming of rehabilitation work on the networks use indicators which, in many cases, include the rate of pipe breaks (Le Gauffre et al. 2005).

The rate of breaks is assessed by tools using statistical models based on knowledge of past failures that have been observed and catalogued (Eisenbeis et al. 2005). These predictive tools require very precise databases, detailing features of the pipes and cataloguing a large number of failures.

The result is that the Care-W integrated system is adapted for fairly large utility services with reliable and comprehensive databases which include a history of failures.

Often, there are too few pipelines and recorded failures in the small or medium network, which means that statistical models cannot be used.

In order to overcome this problem, the SIROCO project was set up to develop an integrated decision support system to prioritize pipes for rehabilitation, which is adapted to small and medium sized companies. This project was financed by the French Ministry of Research and carried out by Cemagref and G2C Environnement between 2003 and 2005. (Bremond et al 2005)

The SIROCO project was based on 3 existing software packages:

- geographic information system "cart@jour", developed by G2C Environnement
- break prediction software "CareW_ PHM", developed by Cemagref
- hydraulic reliability software "Failnet Reliab", developed by Cemagref.

Features of the SIROCO approach

In order to overcome this problem of critical database size, the SIROCO approach involved creating a database that amalgamates data from several companies.

Good knowledge of the network and a structured organisation of information are indispensable in a programme to prioritise pipes for rehabilitation. However, there was considerable disparity between the different utility companies, and for this reason it was decided to base SIROCO on a geographic information system (GIS) which enabled us to advise companies on their information gathering and to structure data organisation.

Small and medium sized companies often have fairly limited numbers of staff in technical and administrative structures, preferring to use people who are polyvalent rather than specialised. Although this may be an advantage in some respects (knowledge of the field, close contact, responsiveness), it can be a problem in terms of the amount of funding potentially available for information management, staff specialisation and ability to ensure continuity in the procedure should there be staff changes. The complexity of the system therefore has to be limited.

On the basis of these three factors (sharing data, using a GIS and limiting complexity), the SIROCO programme was drawn up as follows:

- Definition and collection of data
- Study of the validity of a break prediction model applied to an amalgamated database
- Study of the feasibility of using a model to calculate hydraulic reliability based on data from a GIS.
- Production of a decision support system
- Integration of all tools into the SIROCO software

Definition and collection of data

Design phase

It is necessary to ensure that data from the GIS is compatible with the tools used for predicting breaks and calculating hydraulic reliability, and then to define features common to the three tools.

Pipes

The pipe is the central entity on which the analysis is based. It is at this level that results from the decision support procedure are expressed. Each tool uses a definition of a pipe that matches its own requirements:

- For the GIS, a pipe must consist at least of a unit of line with identical physical characteristics (diameter, material, year of installation).
- For the break prediction software, as well as the pipes having identical physical characteristics, there must also be uniformity in the environment of the pipeline (level of road traffic, type of soil, pressure of service).

- For the software for calculating hydraulic reliability, as it is a hydraulic model, the pipe must have identical hydraulic characteristics (diameter, material) and be situated between two points where flow is modified (pipeline intersection, structure or appliance, point of consumption,…).

In SIROCO the pipe has been defined as a unit that meets all the requirements of each tool.

Nodes

Nodes are not applicable to the break prediction software. For the GIS and the hydraulic reliability software, a node represents the end of a pipe. In the GIS, the node is not affected by any other constraint. For the hydraulic reliability software, the node has significance in hydraulic terms and data is attributed.

Consequently, for the node in SIROCO it was decided to adopt the rules applicable to the node in the hydraulic reliability software.

Failures

A failure is associated with a pipe and can be defined by date, type and cause.

As the SIROCO software is based on an amalgamated database, a precise protocol was established for recording failures, using an incident form (Eisenbeis et al 2002) to ensure that information was collected in a uniform fashion.

As the failure database is linked to the databases of the GIS pipes, history management must be able to handle the inevitable changes in the network which alter the arrangement of pipes. Any failures must therefore be geo-referenced.

Data

So that data originating from different companies can be combined, we must first ensure that it is homogeneous. Given the very wide range of situations and practices, we need to ensure that the collection of information is not affected by subjective interpretation by the different users, while still allowing specific local features to be taken into account.

For the indicators from studies carried out under the aegis of the IWA (Alegre et al. 2000) and the criteria applied in the context of the Care-W project (LeGauffre et al. 2005) certain data had to be acquired, some of which was not available to small and medium companies under current working conditions.

A compromise was sought to satisfy the need to have relevant criteria for a valid database on which to base the decision to rehabilitate, while at the same time using data that could realistically be collected in view of the size of the distribution companies concerned.

Concerning data used in the amalgamated database (diameter, material, date of installation…), it is imperative that all of this data should be accessible to each of the companies, as the absence of information for a single company could render it impossible to exploit the relevant data fully.

In order to simplify this process, the value of some data can be assessed on the basis of references. This is the case, for example, with the roughness coefficient of the pipe which can be estimated initially on the basis of the nature of the material and the installation date. In such cases, the parameters are set and then all grouped together to form a set or corpus of hypotheses.

Collecting information

Sixteen water distribution companies joined the Siroco research consortium. Located throughout France, their networks ranged in size from 14 to 814 km of pipeline.

Data collection was carried out according to the following protocol:

- Digitalisation and integration of each network into the same type of GIS.
- Verification of topology
- Installation of GIS in the company and staff training
- Data collection and entry

After a training session on the different functions of the GIS, we described in detail to the users the variables to be collected, showing the degree of precision required and identifying with them potential sources of information.

Documents providing information on the following parameters:

- Date of installation: dated as-built drawings, municipal archives …
- Soil type: sanitation master plan, geological or hydrogeological studies
- Road traffic: Road traffic figures to identify major axes
- Pressure of service: Reports from use surveys
- Linear loss indices (by sector): Network diagnostic reports
- Pipelines requiring reinforcement: network diagnostic report, development plan
- Elevation numbers: IGN maps, or contour lines (.dwg or other formats)
- Consumption at network nodes: customer billing files
- Failures on pipelines: incident forms (or logbook)

Contact person for complementary information:

- Staff from the water departments (working or retired) for “date of installation”, “soil type” (digging experience), “pressure”, “type of ground cover” (natural terrain, road…), “need for reinforcement”
- Staff from technical and town planning departments for the “coordination with other work” parameter
- Local population for “date of installation” of pipelines

Of the 16 partner companies, only 11 managed to create a data set within the time allocated by the research programme.

Considerable difficulties had been encountered:

- It was very difficult to find exhaustive information on all the variables, though some were essential for the Siroco analysis models to function correctly.
- Responses from the companies were not always homogeneous. In particular, for variables such as soil type or material, we noted considerable variations according to the local context.
- The number of recorded failures that were then integrated into the amalgamated database was insufficient to enable a statistical modelling of the rate of breaks using this database alone

- Company networks contained errors in topology which could jeopardise any hydraulic modelling

At the end of the data collection phase, only 2 companies were in a position to provide a complete set of data.

As a result of these various observations made in the course of the programme, we adapted our tool in order to facilitate the database creation phase.

Adapting the GIS to the structure of the hydraulic model:

- Eliminating ghost pipes
- Creating a typology of nodes
- Producing rules for structuring the network.

Creating tools to assist in the constitution of the database integrated with the Siroco software:

- Tests for topological conformity
- Identifying non-reported objects
- Setting default values

Break prediction model with amalgamated database

Model used

The break prediction model used in this study was developed by Cemagref, Bordeaux (Legat, Eisenbeis, 2000)

The main result from the model is the average number of failures predicted for each pipe over a period in the future.

To obtain this number, first we express the probability of a failure occurring in the pipe according to different parameters (length, diameter, material, soil, traffic…) which may influence this happening. This is a Weibull-type multi-parameter model in which the probability of failure is linked to the values of the parameters. By maximising likelihood, coefficients expressing the influence of the parameters can be calculated. From the resulting function, failure probability can be calculated for all the pipes that make up the network. The average number of breaks per pipe is then obtained by applying a Monte Carlo procedure, which generates failures from the probability function.

Validating the models

To check the validity of using an amalgamated database, models obtained using data from a single network were compared with models based on data amalgamated from several networks.

To compare different models one with another, we used the validity test defined by Yves Legat (Legat, 2002)

The basic principle of the validity test is to compare break predictions with reality, i.e. with breaks that did indeed occur in a period during which observed were made.

To implement the validity test, the period over which breaks were recorded is divided into two consecutive periods, a calibration period to enable the model to be calibrated and a period of validation for which the number of breaks that really occurred is known and on which the prediction is based.

After sorting the pipes into decreasing order of expected number of failures, we present the graph showing the number of failures that actually occurred during the validation period as a function of the number of pipes (Figure 1). The validity indicator of the model is the area defined by this graph. The better able the model is to identify the pipes that are most at risk, the closer the area of the curve is to 1. (A random distribution of the pipes gives an area under the curve of around 0.5)

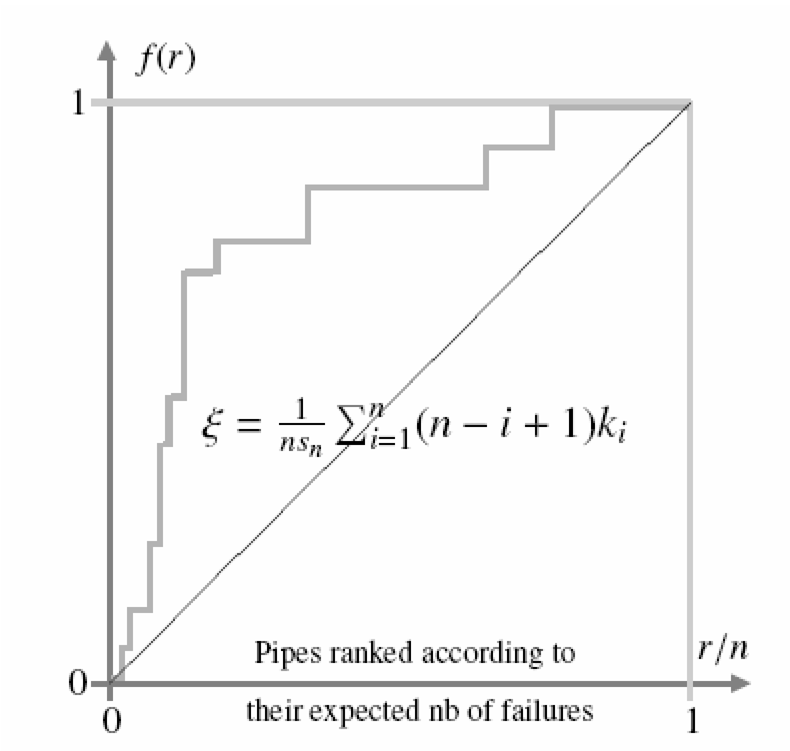

Figure 1 Predictive performance curve (Legat, 2002)

Several series of tests were carried out on fairly extensive networks (more than 5,000 pipes) and on average sized networks (less than 1,000 pipes).

Table 1 Area under the performance curve for large networks

	Network 1	Network 2	Network 3
Model based on data from a single network	0.83	0.72	0.86
Model based on amalgamated database	0.85	0.72	0.81

Table 2 Area under the performance curve for medium networks

	Network A	Network B	Network C
Model based on data from a single network	0.63	0.66	0.58
Model based on amalgamated database	0.56	0.69	0.55

For both the large and the medium networks, by using an amalgamated database it was possible to produce significant models. However, using amalgamated data did not result in models that were more effective than those calculated using data from the networks taken individually.

In the cases we studied, the amalgamation of the data did not appear worthwhile since the data from an individual network was sufficient to calibrate a model.

In the case of small networks (less than 200 pipes), no model was possible unless data was amalgamated. Tests showed that models based on an amalgamated database can be significant.

Hydraulic reliability model with data originating from a GIS

Presentation of software to calculate hydraulic reliability.

The impact of a break in a pipe in terms of continuity of water distribution to users depends to a very great extent on the importance of the pipe in the network as a whole.

Using a hydraulic calculation combined with break prediction, the Failnet Reliab software developed by Cemagref, the HCIj can be calculated, which is an indicator of the impact of failures in each pipe on the volumes distributed to users (Bremond, Bertin, 2001).

$$HCIV_j = \left(\sum_{i=1}^{n} \left(d_i - c_{ij} \right) \times \omega_i \right) \times 3.6 \times tr_j \times \frac{\delta_j \times l_j}{1000} \times \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \omega_i \times d_i}$$

$HCIV_i$ Hydraulic criticality of pipe j in m^3 per year

d_i Average annual demand at node i in l/s

c_{ij} Demand available at node i when j fails in l/s

ω_i Importance of node i

tr_j Unit time for repairing pipe j in hours

δ_j Rate of breaks in pipe j (breaks/year/km)

l_j Length of pipe j in m

C_{ij} is obtained by a hydraulic calculation based on pressure-dependent demand according to the following formula (Bremond et al, 2001):

$$C_i^{\varepsilon}(h_i) = \begin{cases} 0 & \text{Si } h_i < h_i^m - \varepsilon \\ d_i \cdot \sqrt{\dfrac{h_i - h_i^m}{h_i^s - h_i^m}} & \text{Si } h_i \in [h_i^m + \varepsilon, h_i^s - \varepsilon] \\ d_i & \text{Si } h_i > h_i^s + \varepsilon \end{cases}$$

Constraints of network structure associated with using a GIS.

Dividing the network into hydraulic sectors

The basic unit on which hydraulic reliability is calculated is the hydraulic sector.

A hydraulic sector consists of a group of points on the network directly subject to one or several organs (reservoirs, supplies…) which determine the origin of the water distributed and its energy level (pressure).

Dividing the network into sectors is thus a vital stage in ensuring that calculations are valid.

Before doing this, all nodes in the network which fix energy level (reservoirs, source, pumping, pressure boosters, pressure-reducing valves) or limit the distribution zone (valves closed) are identified.

In cases where the hydraulic functioning of the network varies over time, then it should be represented in its most common configuration.

The waterworks systems (from source to storage) make up independent sectors. Calculations of hydraulic reliability concern only volumes of distributed water, they are not valid in sectors that are simply transporting water. When the network is no longer divided into sectors, each pipe should be allocated to its appropriate SIROCO sector.

Basic rules of network topology

Rule 1: Sectors should be independent, in other words no node is common to two pipes from two different sectors.

Rule 2: Within a sector, pipes should all be closely linked, in other words there should always be a route from one pipe to another, linking together any two nodes in the sector.

Rule 3: Each sector should contain at least one pressure-determining node, in other words a node associated with a reservoir or a source. Pressure should be sufficient to supply each node for consumption use.

These topology rules require that the parts of the network be represented in a specially adapted format which does not always correspond to what best describes the physical reality of the network; for this reason, standard models have been used to represent common network configurations.

Decision support system

The decision support system implemented in SIROCO was adapted to the specific features and constraints described above. To do this, it seemed realistic to limit the complexity of the tools used to prioritise sections of pipe that were likely candidates for rehabilitation.

The criteria selected are the result of a compromise between the impacts and opportunities it was hoped to measure, accessible data and the tools available.

Criteria

Two types of criteria were used:

- Impact criteria, which measure nuisance or disturbances caused directly or indirectly by breaks in the sections of pipe.
- Opportunity criteria, which take into account factors that are independent of breaks and which may influence the decision to replace a section of pipe.

Impact criteria

I1: Linear index of hydraulic criticality

I2: Road traffic disturbance index

I3: Repair/Replacement cost ratio

I4: Linear index of losses

I5: Index of local disturbance to continuity of service

Opportunity criteria

O1: Coordination index according to cover

O2: Index of need for rehabilitation

Calculating the multicriteria score of a pipe

For purposes of simplification, simple methods of multicriteria aggregation were chosen to give a single overall score for each pipe.

Since they had different significance, the impact and opportunity criteria were first aggregated separately to give distinct impact and opportunity scores. These were then combined to define the overall score.

The various stages in calculating the score for a pipe were as follows:

- Calculation of the raw value for each of the 7 criteria
- Standardisation of the values for each criterion
- Aggregation of impact criteria then opportunity criteria in order to calculate the impact and opportunity scores
- Standardisation of the impact and opportunity scores

- Aggregation of the standardised impact and opportunity scores, resulting in an overall score
- Standardisation of the overall score of the pipe

Standardisation method

A single standardisation method was selected for all criteria and scores:

$$UXk_i = \frac{Xk_i - \min(Xk)}{\max(Xk) - \min(Xk)}$$, where:

UXki, standardised value of parameter Xk for pipe i

Xki, value of parameter Xk for pipe i

min (Xk), minimum value taken by Xk for all pipes

max (Xk), maximum value taken by Xk for all pipes

If min (Xk) = max (Xk) then, whatever the value of i, UXki = 0

After standardisation, a percentage of the range of values for the parameter is attributed to the pipe. This method was chosen because it is possible to guarantee the dispersion of values for each criteria, which facilitates intuitive assigning of weights (for each parameter, the pipe that is the least critical is assigned the value 0 and the most critical the value 1).

Aggregation Methods

Two criteria aggregation methods were used:

- The weighted sum on a cardinal scale. With this method the user assigns a weight to each criterion and can therefore validate priorities intuitively.

$$SCI_i = \sum_{n=1}^{5} \alpha_n \times UIn_i$$, where:

SCIi, impact score for pipe i

αn, weight of criterion In

UIni, standardised value of criterion In for pipe i

- Lounis and Vanier’s method (Lounis, Vanier 1998). With this method an alternative hierarchy can be obtained, independent of the user.

$$SCI_i = \sqrt{\sum_{n=1}^{5} UIn_i^{\,2}}$$

SCIi, impact score for pipe i

UIni, standardised value of criterion In for pipe i

Two methods were suggested for aggregating the standardised impact and opportunity scores:

- The weighted sum on a cardinal scale, for the same reasons as given above

- A hybrid method combining a product and a weighted sum. With this method the insignificance of opportunity can be taken into account in the case of a low level of impact.

$$SCG_i = USCI_i \times (USCI_i + \lambda \times USCO_i)$$

SCGi, overall score for pipe i

λ, weight coefficient

USCIi, standardised impact score for pipe i

USCOi, standardised opportunity score for pipe i

Integrated software

In order to rank pipes as rehabilitation candidates, the user of the SIROCO software must implement the following procedure, divided into several stages:

- Preparation of database.
- Configuration of a set of hypotheses.
- Production of data files, exported to Cemagref.
- Processing at Cemagref and production of result file.
- Importation of result file by user.
- Definition of weighting.
- Analysis

Preparation of data base

This consists essentially of:

- Testing missing data, especially data that is essential to carry out calculations.
- Suggesting systems for assigning default values when necessary.
- Carrying out conformity tests on the network topology.

Configuring the hypotheses

Before any analysis can be carried out, the user must adapt the parameter settings to local specifics by creating one or several sets of hypotheses.

Default values are suggested for each item of data, and this makes up the set of default hypotheses.

The user can adapt all these values and thus create their own set of hypotheses.

Each set of hypotheses can be saved and restored (including the default hypotheses).

Production of data files, exported to Cemagref

After defining and selecting a set of hypotheses, the user must produce data files needed to carry out the calculations and export them to Cemagref.

Processing at Cemagref and production of result file

The files exported by the companies are stored on a server specific to Cemagref.

Because an amalgamated database is being used, the actions of the various partners have to be coordinated, hence a schedule has been set up:

- Transmission of data for the year n-1: January- February
- Verification and complementary data: March
- Processing and calculations at Cemagref: April – May
- Access to results by water companies: June

Importation of result file by user

A result file is produced for each company, and they alone can download their file, using a specific access code.

Definition of weighting

To define weighting, the user must first choose the parameter aggregation methods:

- Calculation of impact and opportunity scores using the weighted sum method or the Lounis and Vanier method
- Calculation of the overall score using the weighted sum method or the hybrid method.

He must then assign the weighting required for the chosen method. As for the set of hypotheses, a default weighting is provided, the weightings created by the user can be saved and a new weighting can be created by duplication/modification of an existing weighting.

Analysis

To carry out an analysis, the user selects a context and a weighting, he can then carry out several analyses from the same context.

Results can be accessed in different forms:

- List of all pipes sorted by decreasing standardised overall score with detail of standardised values for each criterion, impact and opportunity scores and overall score.
- List of the most critical x% of pipes with values for their main characteristics (Year of installation, diameter, material, length) and estimated rehabilitation cost.
- Graph showing pipes by class according to the overall score value or based on their belonging to the most critical y%.

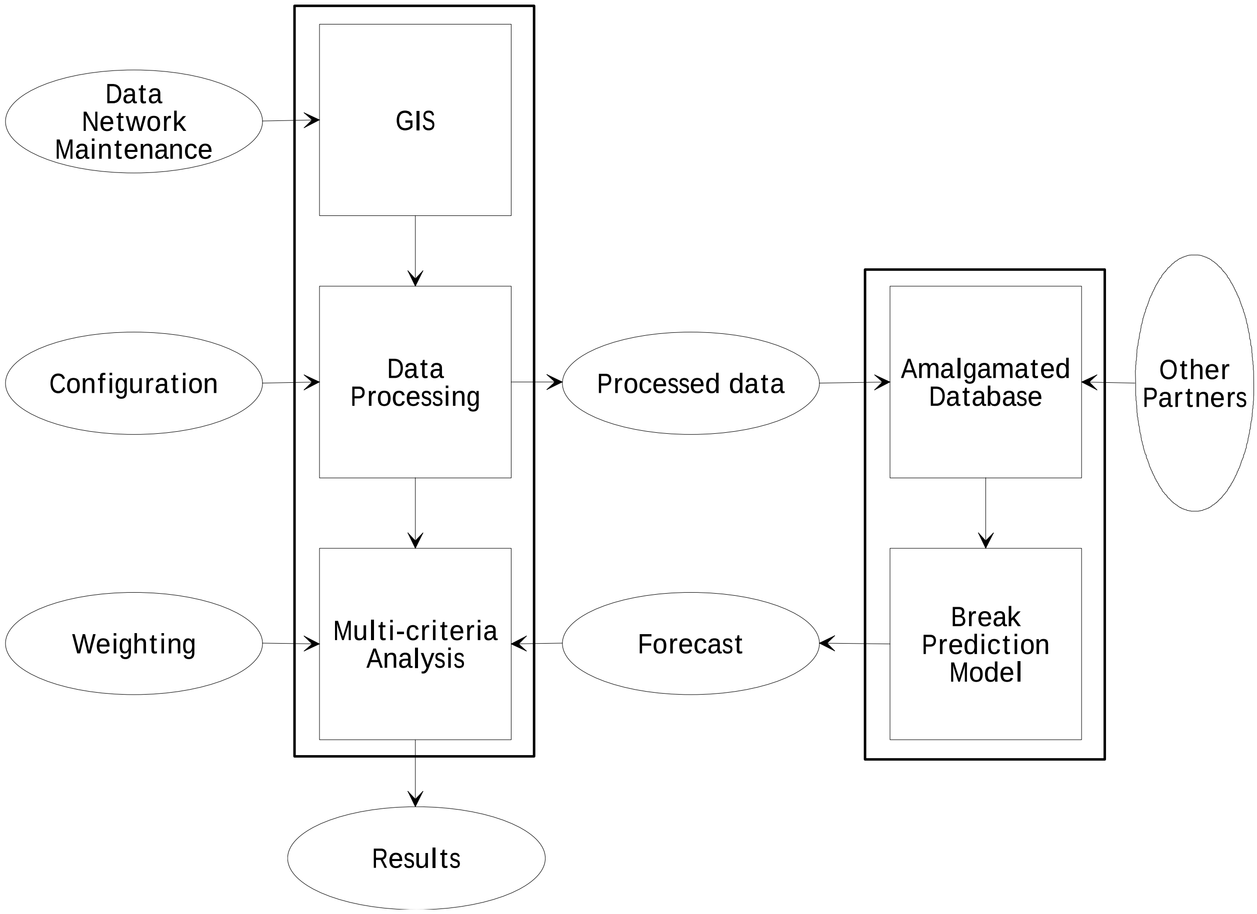

Figure 2 Data flow and processing

Conclusion

The aim of the SIROCO project was to produce an integrated decision support system for prioritising drinking water pipes as candidates for rehabilitation, which was suitable for small and medium sized companies.

Our studies showed the feasibility of using an amalgamated database to forecast breaks using a statistical model.

It was also demonstrated that, provided certain topological rules are respected, it is possible to carry out hydraulic reliability calculations using data from a geographic information system.

When putting the project into practice, it was found that the partner companies encountered difficulties in creating the databases needed in order to be able to use the statistical tools. Only 2 partners out of 16 were able to produce databases that conformed to requirements within the project's time schedule.

As a result of this project, the SIROCO software is to be marketed.

To meet the needs of medium-sized companies with databases that are sufficiently large to obtain results from break prediction models, an “autonomous” version of the SIROCO software will be offered.

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