A ROADMAP TO EXTENDING GIS FOR PUBLIC UTILITY COMPANIES

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Abstract Emergency management, leakage handling and maintenance of distribution networks are among the most essential tasks a public utility faces. Geo information systems are frequently employed to document the state of the network and the location of leaks and line failures. We propose to make the transition from the essentially documentary character of existing systems to a decision support perspective. This will give additional use and utility to information already stored and provide for more efficient decision making.

Keywords: Public Utility Company, Gas Maintenance Management, Spatial Methods on GIS

1. Introduction

Up to the year 1998, German legislation provided utility companies of all sorts with a state sanctioned monopoly within its alotted distribution region. Competition was regarded jeopardizing the reliability of supply rather than a means of efficient resource allocation.

Issued in compliance with EU requirements, new legislation as of 1998 and 1999 has completely changed this situation. As a step towards an open EU-wide energy market for electricity and natural gas, access to distribution networks and to the end user has been almost completely liberalized. A market was created almost overnight.

These legal steps have - upon first sight - not changed the market structure substantially. Only five percent of all customers have in fact switched to new providers, but it must be seen that those have been the large consumers within the production industry and related sectors. Also, the effect upon the price structure has been a profound one: margins and ROI have been diminishing on a broad scale as new suppliers keep entering the market and an EU wide spot market for production capacity has formed. Rising cost of energy and pollution taxes will probably make consumers even more price sensitive and volatile in the future.

Taking it all together, utility companies of all sorts are required to tightly control their costs of operation. With no chance of quality differentiation in the eye of the customer and no substantial differences with respect to the price of primary energy bought, construction and operation of distribution networks becomes one of the key sources of operational profit.

With customers giving prime importance to the reliability of supply, maintenance of distribution networks becomes one of the key sources of competitive advantage and operational profit and is no longer a secondary activity (Aselmann [2]).

Electric utilities have been among the forerunners of GIS implementation. Most of them have used GIS for years to document line and transformer locations. Despite their substantial costs, most GIS have done little more than replace the ink-drawn maps of past centuries. It is our tenet that utilizing what data are stored in a GIS for planning purposes can unleash a large cost saving potential without even interfering with every day operations.

The ultimate goal of our research will be a toolbox of analytical, spatial-oriented methods that is closely linked to existing, query oriented methods via a common user interface. State-of-the-art GIS are typically based upon (object-) relational database systems and feature an open architecture, which makes our task a lot easier. Spatial data can be retrieved from such databases through well documented and reliable SQL extensions such as SQL /MM. Results can in turn be displayed within the maps provided by the GIS. Large database supplies have coined the notion of a "data cartridge" or a "data blade" for a set of methods specifically geared towards supporting specific application domains.

Commercially available cartridges are normally restricted to rather low level, utility-like functions, such as calculation distance between geometrical shapes. We are proposing to extend this architectural model to build decision support systems that are flexible, easily adapted to company-specific requirements and can be introduced "on-the-fly", e.g. without interfering with day-to-day operations.

In this article, we illustrate this approach with a cartidge for leak management in the natural gas distribution network. The extension to power line failure management seems straightforeward, but is far from trivial due to the more complicated structure of electricity distribution: Different voltage regimes, transformer location and characteristics, operating characteristics of power plants and questions of state estimation are just some of the more serious problems. Other applications of the cartridge concept include location planning for transformers / pressure regulators or emergency management during natural catastrophes.

The remainder of this article is organized as follows: In section 2 we shall give an overview of how maintenance management in gas networks is carried out. A prototypical software tool to support those activites is outlined in Section 3 together with its underlying algorithms. Section 4 is devoted to the software architecture of our prototype. Extensions to the concepts will be briefly covered in 5, and we shall close with a summary in Section 6.

2. Maintenance of gas pipelines

Reliability of supply and low operating cost are the two prime targets of pipeline operations. Preventive maintenance typically forms the lion's share of all cost components. Suddenly arising, large and dangerous leaks do occur and must be treated immediately through emergency action. They do not account for a substantial part of the cost, though, and cannot be planned in advance. They do not form our focus. It is however not uncommon to combine emergency and preventive measures for reason of cost saving.

2.1 Maintenance procedures

Inspection and leakage check for a gas network is done on a regular, scheduled basis by trained and properly equipped staff. Additional leaks are discovered through unsystematic detection by the public. Leaks are caused mainly through corrosion of metallic pipes, faulty junctions (especially corrosion of sockets), improper excavation activiy or heavy traffic load. Incorrect procedures during the initial laying of the pipes is the other main reason. (see Fig. 1, (VNG [10])

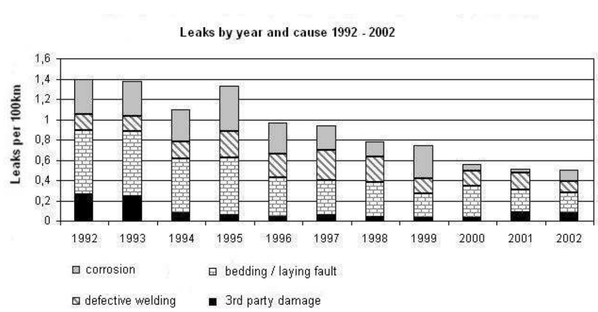

Figure 1. Leaks per year and cause for VNG's network

Once detected, leaks are assigned one of 4 classes according to the amount of leakage and their building proximity (see DVGW [5] for details). Only class A leaks call for immediate emergency action. All other leaks present cost problems rather than immediate danger and can in principle be dealt with in conjunction with preventive maintenance.

To avoid the cost and labor intensive process of earthworks and a complete re-laying of pipes, several in-situ techniques have been developed, which, depending on characteristics such as a pipe's age and overall condition and the number of stub lines may or may not be applicable for a particular case (see 3.2 for details). These techniques offer the additional benefit of keeping traffic and neighbor disturbance to a minimum.

2.2 Maintenance cost

Only about 1/8 of the total repair cost is on account of material and on immediate labor for pipeline replacement respectively. Another quarter is spent for earthworks, while - at least in built-up areas - a surprising 50% goes to reconstruction of the road surface (for the classic dig-and-re-lay-technique). This clearly advocates all pipe and line replacement within one road to be done simultaneously. Considering the whole bunch of measures, preventive replacement of a line may become economically feasible years before it has reached the end of its useful life, as calculated for the line in isolation (see section 3.1).

This observation opens up large savings potential and calls for close cooperation between different utility companies (electricity, gas, phone). Reaping those benefits is primarily a problem of process organisation and cross-organizational coordination and shall not be considered further in this article, but is certainly part of active research at our institute.

All cost elements must be split up by fixed and variable components. Construction site setup costs are to a large extent size independent and hold a substantial share of total maintenance costs. By pooling several activities within local proximity, degression of total cost per site can be achieved. Considering the long backlist of existing leaks, which can amount to several hundred within a large city, and the still longer list of preventive replacement measures, this calls for a computerized decision support system. We shall concentrate on this problem in the sequel.

3. Decision Support System for maintenenance management

Fig. 2 illustrates the overall structure. In a first step, each line segment and known leak is classified for its urgency of refurbishing and assigned a respective score. Technical considerations such as pipe condition and material will suggest the optimal technique (were this segment treated in isolation) and render other refurbishing techniques infeasible altogether.

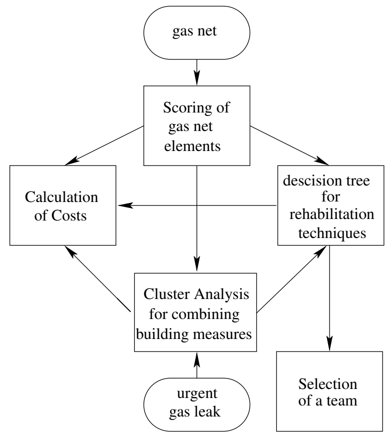

Figure 2. Concept of the Tool

Segments are clustered next and a joint technology for the whole cluster is determined. Clusters are formed where overall savings can be realized. For reasons of traffic obstruction and site manageability, we do not allow clusters to grow beyond a certain size.

A team is assigned to the site by matching technology and size of site with team qualification.

Immediate action leaks are handled as special cases. If such leaks are found within the center of an already identified cluster, the whole cluster is given immediate treatment. Otherwise an emergency team is assigned to cope with the problem in isolation. Figure 3 illustrates such a natural cluster of leaks.

3.1 Scoring of line segments

Priority scoring for preventive maintenance has been well researched within civil engineering context. Mostly only factors "on file" are considered during calculations and no on-site inspection is required.(DVGW [3]). Typical influence factors from the technical side include:

- pipe diameter
- leaks per km for this line versus average value for whole city
- distance to buildings
- unfavourable, high-stress routing of segment
- unfavourable soil conditions

economic factors

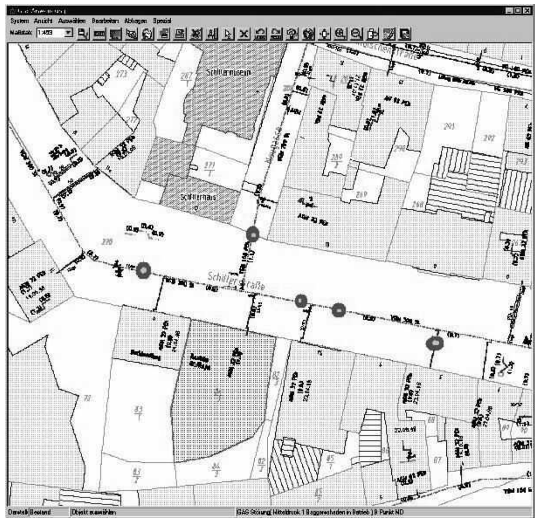

Figure 3. An example where leaks form a natural cluster

- outdated material
- outdated diameters

and among external influences

- traffic load (which may change substantially during the frequently over 70 years of lifespan)
- unapproved / illegal tree cover (a problem that is very important with sewer pipes)

Normal, linear scoring systems are based on a catalog of citeria that are given an individual score and after that aggregated to a weighted sum to arrive at a total score. See fig. 4 for a typical, real life example (gray pig iron pipes)

3.2 Selection of maintenance technique

Maintenance techniques are classified as repair, reconditioning or replacement measures. Repair is concentrated upon the point of failure, most often leaky junctions and bushings. Typical reconditioning techniques try to refit existing pipes with a new, tight and smooth inner lining, either through liquid resin spraying or plastic hose relining. If the pipe is in overall good condition, spraying may be concentrated on junctions.

Replacement can also be done through methods other than the "dig a trench" technique. So called trench-less techniques will dig only two small pits at each

criteria	graduation of criteria			
diameter	DN < 80	DN 80 – 100	DN 125 – 150	DN > 150
soil type	disordered cohesive	disordered non–cohesive	homoge–neously cohesive	homoge–neously non–cohesive
traffic load	heavy load traffic (HLT)	residential road	sidewalk / cycleroute next to HLT	sidewalk / cycleroute next to residential road
building distance	< 3 m	3 – 10 m	10 – 20 m	> 20 m
leak rate history	>= 1 leak per km and year	> 0,2 leaks per km and year	> 0,1 leaks per km and year	<= 0,1 leaks per km and year
weight	5	3	2	1

total score for pipe indicated by profile is 5 + 2 + 5 + 1+ 5 = 18

Figure 4. Score for the line segments (DVGW [3])

end of the pipe and either destroy the old pipe underground by a burster to create space for a new pipe of same diameter or use the old pipe as a duct for a new one of less diameter. As the gas flows faster within plastic pipes with their smooth surface than it does within old iron pipes, diameter reduction is often tolerable.

Line segments with many T-crossings or consumer connections are considered unattractive for inlining, as each such spur needs manual treatment and its own pit.

Depending on soil condition and material of the old pipe, bursting may carry high risk. The debis of a bursted pig iron pipe display sharp edges that may seriously scrap or even puncture the new plactic pipe as it is drawn along.

All trenchless techniques can only be applied where lines run straight or at most very smoothly bent.

Those are just a few examples of the many boundary conditions to consider during technology choice. Most of the data required can be retrieved from the GIS and its associated non-geographically oriented databases, though. Material, age and diameter of pipes can be retrieved in a straightforward fashion. Parameters such as building proximity and number of consumer connections per km call for standard spatial extensions to regular SQL but still are retrieval tasks, a road's traffic load can be retrieved from the GIS operated in the department of roadworks. Ambient conditions such as soil or tree cover will have to be entered into the GIS after on-site inspection or can be retrieved from ordinance survey data.

Technical requirements for the new pipe (especially its capacity) will depend upon network extension planning and future demand along the renovated line. Where demand is dominated by few large consumers, there is no alternative to personal contacts, but where consumption is through a sufficient number of small customers to warrant statistical treatment, automated demand forecasting may take place. Putting the pieces together, we are faced with a complicated, but rather well structured decision problem. Considering the task at the utility company level, the dataload is heavy, but can to a large extent be fulfilled from existing systems.

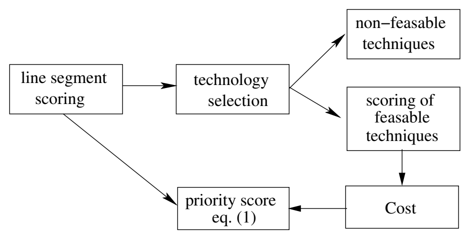

Figure 5. Decision Support System

The Decision Support System we propose is outlined in figure 5. Given the characteristics of the line segment, infeasible refurbishing activities are filtered out in step 1. The remaining alternatives are subjected to cost calculation (see section 3.3). They can now be presented to either the decision maker or the clustering algorithm sorted on cost or other user-specified criteria. For each maintenance activity and technology, we may also calculate the metric

```
Maintenance Productivity MP :=
  "urgency Scorepoints remedied"
     (as calculated in 3.1)/
  Cost incurred                                  (1)
```

which can guide the priorization and budget allocation process by showing where money is spent in the most efficient manner.

As for the internal DSS operation, a "classic" rule based expert system or a decision tree seem to be the two most apt technologies for the filtering process of step 1. Such rules can be derived semi-automatically from the analysis of past maintenance records. A typical rule would be:

```
  diameter < 100
∧ pipe material = 'gray pig iron'
∧ distance to other pipes > 1m
∧ number of consumer connections
  < 0.03 per meter
```

$\wedge$ `higher capacity needed ='yes'`
$\wedge$ `straight routing`
$\longrightarrow$ `burstlining technique`

3.3 Cost calculation

Cost caluculation is among the standard tasks of controlling. It is important to realize that main cost drivers are different for different reconditioning techniques.

Traffic intensity and unusually narrow roads are heavy cost drivers for trenching technologies, where pits must be secured and traffic diverted, but lose much of their importance with other techniques, while the picture is completely reversed considering "consumer connection density along the line" as a cost driver.

Nevertheless, most of the cost influence for all technologies is captured by no more than a dozen of site characteristics, most of them can be taken directly from the GIS. This is patently proven by public tender processes where civil engineering taks are described by just a few parameters to base quotations on.

Price levels will of course be dependent upon the region considered and level of competition among resident construction firms. Those are non-universal parameters that must be entered into the system by hand. Yet they are few in number and can be recovered from the analysis of past quotations should direct data collection not be possible.

Should a line be replaced before the end of its useful life, its current value is lost and must be seen as an additional cost component. This is an easy task for lines where construction cost, age and depreciation are on file, else this numbers must be estimated. The estimate for useful life will usually be based upon well known parameters such as material, diameter, age, soil conditions and traffic load. If original construction costs are not available or completely outdated due to inflation or technological progress, taking an opportunity cost perspective seems perfectly appropriate. This amounts to taking for yearly depreciations what value we would have if we had current pipe technology installed today. (see figure 6).

If the new pipe is going to replace a leaky one, we must also take into account avoidance of gas losses as a cost component. We suggest subtracting avoided loss from the cost of each construction project (also within formula (1)). Regarding the time frame: should maintenance planning be done on a monthly basis, we would of course have to subtract monthly losses, etc. Losses im m^3 can be estimated from leak classification (see section 2.1), to get the monetary value, we multiply by our cost price.

While this whole procedure may seem rough and ready, it is sufficiently precise for our task of priorization and amalgamation of mainatianance activities. It is not intended to generate figures for financial accounting.

Segment	Cost of production	remaining lifetime	is layed
A	2500	20	1999
C	unknown	unknown	unknown

lifetime (C) estimated from material = 12 years
depreciation (C) = ?
deprec. per year if newly built today = 20
--> current value (C) = 12 years * 20

Figure 6. Calculation of current value of a segement

3.4 Clustering: general considerations

Pooling of maintenance sites is attractive form the cost perspective as it helps reduce fixed cost,but standard off-the-shelf clustering for local proximity will not do the job due to several reasons:

1 Pooling shows its maximum benefits, when all refurbishing is done using the same technology. The most cost efficient technology for A and B together may be neither optimal for A nor B in isolation. In other words: Technology choice and cost calculation must be redone each time an amalgamation is considered.

2 With total cost being dominated by earth works and surface reconstruction (in open pit technologies, see section 2.2), pooling activities may be beneficial even when ultimate pipe repairs are technologically unrelated. Once dug out, work on the high pressure distribution net must be done by specially trained and licensed personnel. Even so, jointly maintaining low and high pressure pipes can reap most of the pooling benefits.

3 Chaining is a phenomenon well known within cluster analysis, which can have detrimental effects on the quality of automatically generated cluster solutions. Line segment B is pooled with A for its pooling benefits (not so much for its own urgency), now C becomes attractive for its pooling benefits with neighboring B and so on. The solution is eventually dominated by few, very large construction sites. This is an undesirable phenomenon because (a) large sites create disproportionate traffic obstruction and put undue stress on the resident population and (b) the assumption of saving fixed cost through pooling breaks down when total construction site exceeds a certain threshold and (c) citizens are eager to ascertain an equal maintenance quality of lines across a city.

We have solved problem (3) by requiring total construction site size to be below a certain threshold as measured by (weighted) line length under maintenance.

Open pit stretches are given a weight of 1, while tube relining for example is given one of .3 due to the less obstructive nature of the technique.

As a first step to tackle problem (1) and (2) a savings matrix is derived and stored which gives rules for calculating what cost components a pooling of site 1 (using technology A) with site 2 (technology B) creates. (see Fig. 7 for an example). The most favorable technology (or technology mix) to handle A and B jointly (problem 1) can now be easily derived through enumeration of all technologically viable alternatives. Note that the matrix is technology dependent only and thus moderate in size and must be derived only once to be stored in the GIS database for retrieval.

Tech Site A → / ↓ Tech Site B	Inlining	open pit low pressure	...	open pit high pressure
Inlining				
open pit low pressure	(2)			(1)
...				
open pit high pressure				

typical rules

for element (1) savings = 1 * construction site setup cost
+ earthworks[1]
+ roadworks[1]

for element (2) savings = 0.3 * construction site setup cost[2]

[1] for the shared lenght of the trenches as taken from GIS

[2] savings downweighted due to different equipment requirement of both technologies

Figure 7. Savings matrix prototype

Not withstanding the restrictions imposed by problem (3), the pooling process should be guided by the quest to either maximize cost savings directly or alternatively the derived metric (Eq. 1), as MaintenanceProductivity increases from

```
MP1 = (scoreSite1 + scoreSite2) /
        (costSite1 + costSite2)
```

to

```
MP2 = (scoreSite1 + scoreSite2) /
        (costSite1 + costSite2 - savings)
```

In any case, our objective function is certainly substantially different from typical clustering problems where the majority of popular objective functions are based on proximity of points as measured by Euclidian distance.

We have scanned the literature to propose solutions to this problem.

3.5 Cluster algorithm GDBScan

DBSCAN (Density Based Spatial Clustering of Applications with Noise) has been proposed by (Ester [6]) as a powerful density based clustering algorithm. In its basic version, points are seen as spread out in Euclidian n-dimensional space. Cluster nuclei are formed by regions of high density as measured by the concept of an ε-neighborhood. Every point that has more than MinPts other points within a distance threshold of ε is considered dense[1] and (together with its MinPts(or more) ε-neighbors) forms the center of a new cluster. This cluster grows as the ε-neighbors are in turn checked for being dense points as well by examining their respective ε -neighborhoods, and so on. Once a cluster has stopped growing, an arbitrary hitherto unassigned point is chosen and tested as candidate nucleus of a new cluster. Upon termination of this briefly sketched algorithm, each point is either (see fig. 8 for illustration):

- an inner cluster point with MinPts or more in its ε-neighborhood (A)
- a point at the boundary of the cluster (e.g. a point which lies in the ε-neighborhood of an inner point (B)
- a singleton (neither of the above, lying in a low density region) (C)

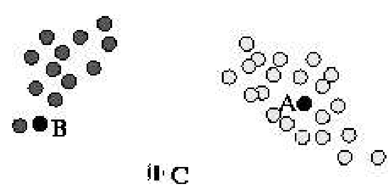

Figure 8. DBScan Cluster

DBSCAN has displayed superior performance in finding clusters of all shapes[2] as long as the underlying space is 2- or 3-dimensional (Josiger and Kirchner [7]) and scales well with N, the number of points. Running time is O(N logN) when efficient spatial access methods such as R-Trees are employed. The number of clusters is determined through the algorithm.

GDBSCAN (Generalized DBSCAN) as introduced by (Sander [9]) generalizes the concept of an ε-neighborhood by replacing the Euclidian with an arbitrary quasi-distance function[3] between two objects. Furthermore, points

[1] MinPts and ε are user specific parameters.
[2] As gas pipes normally follow the road grid, we cannot expect to get circular clusters from pooling.
[3] As triangular inequality is not required to hold, this function need not be a distance in the topological sense of the word.

within this ε-neighborhood are not simply counted and checked against the MinPts threshold, but they are assigned unequal weight according to a "similarity function" measuring their similarity to the core point. This function may depend upon spatial and non-spatial characteristics of the two objects. Sander gives the details down to the pseudocode level.

We have used travel distance along the pipe network as a pseudo-distance function between two construction sites (closely related to well-known Manhattan distance) and have set ε to 1 km, which is indeed a typical threshold for pooling of directly neighboring sites. Monetary savings or Maintenance-Productivity increases can - after suitable normalization - serve as a similarity function.

Preliminary results with small networks show very promising and plausible results, yet some work remains to be done as the choice of ε and MinPts will seriously affect the solution and is not a trivial task.

4. Tool prototype

In the vein of a classic decision support tool, all information generated is meant to ease human decision through sensible proposals, not to replace it. Intuitiveness of the user interface and ease of manual intervention are core components of the system. Fig. 9 shows how our prototype is structured. Oracle Spatial 9i has been chosen as an object relational database system. Spatial extensions to standard SQL allow for direct storing and retrieval of spatial objects. As to the list of spatial object types and their respective access functions, Oracle adheres rather tightly to OpenGIS and SQL/MM standards, making porting the prototype to other platforms an easy task. Typical functionality al-

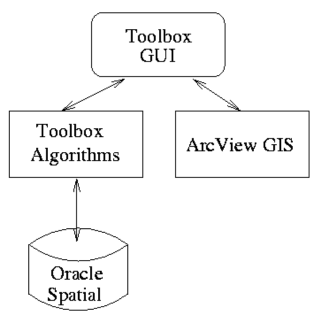

Figure 9. Structure of Prototype

lows for defining elementary geometric shapes such as lines, multi-lines (built from straight segments) or polygons. An object may carry both geometric and non geometric properties. A gas pipe might thus be modeled as a multi-line with diameter, material and age as non-geometric attributes. Adjacent pipe segments can be modeled through a relation to their representing multi-lines. Typical query functions allow for area calculation, adjacency queries or distance calculation between spatial objects. To calculate the distance between two streets one would for instance use the function SDO_DISTANCE and write (Oracle [8])

```
SELECT SDO_GEOM.SDO_DISTANCE
     (a.shape, b.shape, 0.005)
FROM street a, street b
WHERE a.name='main street' AND
      b.name='zeiss road';
```

To our experience SQL/MM does to our GIS/DSS what normal SQL does to standard database applications: it relieves the programmer from the chore of programming and optimizing low level access functions.

Building the whole system on SQL/MM and Oracles procedural extensions is not an option though due to severely limited semantic power and 3rd party toolbox support. Realizing what has been described in Section 3 of this paper in a general purpose object oriented language seems a lot easier. We have chosen Visual C++ for the language and used Microsoft foundation classes to provide non-geographic GUI and windows functionality. SQL/MM commands can be sent to the database via a standard embedded SQL interface. Being a research prototype, we are using ArcView as a geographic visualization tool. ArcView uses a proprietary data model and is based on a file- rather than a database storage model. Interfaces to ArcView are well documented, though, and the software boasts ease of operation, a powerful user interface and widespread acceptance. We have found its function to overlay topographic or thematic city maps or ortho photos especially useful. A commercial system would probably write results to the Oracle database and draw all visualization information form there.

Fig. 10 shows a typical screenshot.

5. Functionality extensions

Gas leak and maintenance management are just the first steps towards a fully fledged toolbox for public utilities. Next step planned is a maintenance toolbox for water and electric utilities. While water needs only minimal adaptation, electricity is more complicated:

1 Faulty lines are normally not detected through visual inspection but through analysis of continuous measurement of electric parameters (voltage, current, phase) at certain spots in the network. Goal is to pinpoint the fault location with a minimum of additional measurement. This calls for extensions to an engineering discipline that has become known as "state estimation", see e.g.(Abur [1]).

Figure 10. Typical Screenshot

2 Maintenance techniques are totally different.

3 We have to deal with at least three voltage regimes (high, medium, low) and their corresponding networks, the interconnecting nodes being marked by transformer stations.

4 Transformer stations and measuring devices can be faulty too. This is especially problematic, when defective equipment erroneously indicates line failures through state estimation.

A totally different line of functionality extensions is catastrophe management. Recently, floods have posed serious problems to several cities of Western Europe. GISs that have stored a digital terrain model can automatically identify endangered regions should the river rise to a certain level (see fig. 11).

6. Summary and outlook

Extending GIS functionality through the tools described will make the transition from a mere information to a decision support system.

Most current GISs are based on object relational database systems. This systems, when equipped with extended geo-spatial functionality, provide a strong and performant integration platform. Displaying results in windows GUI and GIS maps is achieved without serious difficulty.

Maintenance and leak handling in gas networks has been used as a prototype. This is an application of medium complexity with immediate utility to the end user. It has been realized that this problem can only be solved through close interaction with quite disparate fields of research: the technicalities of

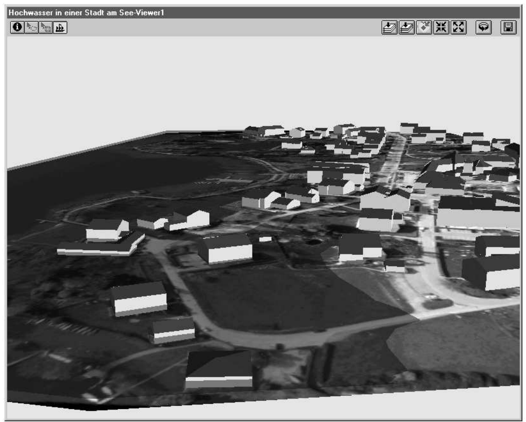

Figure 11. Flood simulation with GIS

pipe refurbishing, economic considerations to identify key cost drivers and the algorithmic side, where new clustering algorithms had to be developed and deployed. This interconnection of different fields makes research attractive. It may on the other side have hampered widespread commercial deployment. As we have found, this effort needs be made only within the development phase. Everyday use of the system is easy and fully integrated with standard GIS operation. Altogether, GIS/DSS are commercially viable projects.

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