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The water supply network analysis tool KANET

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Abstract

Statistically, the greater part of water supply systems' costs is due to distribution. Two classes of models are available for the analysis of distribution networks. First, *simulation,* the 'hydraulic network balance', treats existing or planned systems whose dimensions and input are known. Simulation has also been extended to include the system's dynamic hydraulic behaviour, tracing also the propagation of water quality. A second class of models utilizes *optimization* to design a new network. Cost optimal diameters, pumping heads, inflow rates are determined employing principles of Operations Research, observing constraints including pressure and demand, flow velocities, and the hydraulics defined by the simulation model. Once a cost-optimal design has been determined based upon a 'design demand' it may still appear desirable to verify network operation under different demand patterns. KANET offers both, *simulation* and *optimization.* Operation of the package is guided by a user interface, facilitated by graphics, a database providing connectivity. The simulation algorithm, a Newton-Raphson iteration scheme solving a set of simultaneous linear equations for unknown flow correction terms, is time extended including the propagation of water quality. Optimization is by four modules. TREEOPT optimizes a branch network using Linear Programming, TREEALL evaluates the total number of branch networks of a reticulate system. For larger networks TREEGEN, a genetic algorithm, improves a population of optimal branch networks converging towards the global. The result may serve as input to FLOWGEN, a second genetic algorithm, performing an optimal adjustment of flows restoring branch networks to reticulation. The paper is descriptive and does not reiterate mathematical formulations presented elsewhere.

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1 Introduction

Urban water supply systems can be separated into three areas of engineering. First, there is raw water intake leading, second, to water treatment. The greater part of investment and maintenance cost is, third, due to water distribution including highlift pumping, standpipes, boosters, valves a.o. hydraulic control units. Extensive modeling has taken place in this area being still a focus of continued research. Two classes of systems analysis tools are proliferating, *simulation* and *optimization.*

Network *simulation* came historically first. Modeling the hydraulics of an existing network, synonymous for 'network balance', is to determine flows in the lines and pressure at the nodes of a fixed system with given demand and input. Simulation serves to identify network deficiencies, to allocate unaccounted water, to support network rehabilitation and planning decisions. Simulation is still considered the primary tool for network management and control. With the hard- and software available limitations of the calculations are hardly encountered to-day concerning network size, inclusion of various hydraulic features, convergence time. Difficulties arise in the realm of model calibration. Numerous model parameters and system's constants are to be determined. Networks in need of analysis, by definition, are in need of data. Notorious data bottlenecks usually exist as to the roughness of pipes installed 'some time ago', and with respect to consumption data allocated to nodes in space and time.

Optimization is the goal of the second class of network tools, historically second, though a network ought to be designed prior to simulation in the first place. In case of straightforward design optimization cost optimal diameters and pumping heads are to be determined subject to peak demand serving commonly as a design criterion. Constraints include minimum supply pressure to be maintained at the nodes, maximum velocities to be observed in specific lines, hydraulic formulae and systems functions. In addition to the input known from simulation optimization requires investment and operation cost data, present value factors implying an economic time horizon and future interest rates, in order to achieve an optimal trade-off between present investment and future operation cost. Since the mathematical formulation of network optimization is nonlinear and integer, nonconvex and multimodal a multitude of optimization concepts and solution algorithms has been proposed over time, often conceived as a sequence of algorithmic steps [1,2,3]. This strategy has also been adopted in KANET. The resulting separate modules preserve greater flexibility performing the network analysis.

A third area of network systems analysis must be mentioned being not part of KANET. *Control* is to facilitate automation, to minimize energy and operation cost, reduce the switching of large pumps. Optimization algorithms successfully used in this context include Discrete Dynamic Programming [4]. The resulting control strategies extend over a time span of one or several days. In addition, forecasting models must be available predicting water consumption during the control period. Other system's properties are required to make control a success. A satisfactory standard of instrumentation, gauging, remote control facilities, monitoring and display - Systems Control and Data Acquisition - is a necessary prerequisite. Different power tariffs and sufficient clear water storage must exist in order to accomplish energy savings by control. In practice control is also implemented by experienced operators utilizing but few key parameters. Adequate technical standards and maintenance of a system may make the effort of comprehensive control appear in parts redundant.

2 Algorithms

Presently, the state-of-art is to implement efficient hydraulic network simulation algorithms based upon Newton-Raphson iteration schemes solving a set of simultaneous linear equations, performing the hydraulic balance at once for the entire network. Prior estimates of either flows and/or head losses are useful. The efficiency of the algorithm depends upon which of the two parameters, flows or pressure, was chosen to be unknown.

KANET employs the concept by H.B. Nielsen [5] introducing flow correction terms of an initial flow estimate, obtained from a spanning tree, thus reducing the number of unknowns to the number of loops. The resulting symmetrical Jacobian matrix is rearranged upper triangular, the diagonal carrying the sum of head loss-flow ratios for any loop. The algorithm is fast, convergence is safe. Special effort was taken to model hydraulic control and operation units encountered in practice - water towers, high-lift pumping, booster, throttle control valves, check valves, pressure reducing valves - also introducing 'pseudo' lines and loops modifying the graph to serve as the basis of the Jacobian matrix.

Modeling the system's dynamic behavior with time variant supply and demand, and including the propagation of water quality, e.g. chlorine or hardness, is known as 'extended simulation'. The prevailing velocities in water distribution networks justify the approximation of time variant flows and head losses without resorting to non-steady-state formulations. Supply and demand are taken to be constant during time increments displayed by step functions extending e.g. over an hour. If the water levels in the storage tanks constituting the hydraulic reference state parameters, differ in the hydraulic network balance at the end of a time increment compared to the beginning, a correction run is supplemented reducing the water level difference to a desirable limit. Otherwise, the time increments are reduced.

The approach used to superimpose the hydraulic simulation with a water quality parameter, either conservative or decaying, is the 'event-driven' method by Boulos et al. [6]. It introduces the definition of time dependent 'hydraulic' and 'subhydraulic' events, the former being exogenous, e.g. change of consumption and supply input, the latter endogenous denoting the arrival of a 'quality separation front' SEP at a node, having traveled the distance of a 'segment' or SEG. A hydraulic event is rearranging travel time and velocities. The input concentration of a quality parameter may change at any event.

Concerning the network optimization introduced above Linear Programming is generally recognized and established being the appropriate solution technique [1,7,8], and can be regarded a fortunate algorithmic option. The algorithm delivers cost optimal integer diameters, without distorting assumptions, if the flows are known, e.g. if the topology of the network is a 'tree' [8]. This is true for gravity feeding as well as pumped supply. A 'tree' or branch network, by definition, must not contain any loop permitting alternative supply to any node. Water supply network optimization is preferably applied to the system mains represented by the arteries of the system.

Smaller diameters connected to the mains and serving as subdistribution, their size depending on the population density, are commonly fixed by standards and cannot be further reduced. This has two implications. The subdistribution of smaller diameters is available for an alternative supply of nodes - answering the need for safety of supply - in case the system of mains forms a 'tree'. Second, the fact of placing two diameters of adjacent size in the same line resulting from Linear Programming [7] is acceptable practice and commonly encountered economy considering the main arteries.

It can be shown that any 'tree' or branch network, containing the nodes of the reticulate system constitutes a local cost optimum of the reticulation [9]. Hence, total evaluation TREEALL of the existing trees of a looped system (whose total number is known) will deliver the global solution by comparing the local minima. This procedure is not amenable if the total number of trees is too large. TREEGEN, a 'genetic algorithm' and/or 'evolution strategy' is employed to improve the topology of a population of branch networks towards a globally optimal topology. This is by utilizing mechanisms of biological evolution encompassing mutation, recombination, selection. It proved advantageous here to combine the philosophy of genetic algorithms and evolution strategies by choosing a physical item (the chords of a reticulate graph) consistent with evolution strategies [11] to be associated with a binary variable ('yes' or 'no') consistent with genetic algorithms [10].

The main arteries of existing urban networks usually show a tree shape topology representing a branched system, safety of supply being provided by secondary lines. Though, for a variety of reasons a reticulate main system might still be desirable. Accordingly, FLOWGEN, a second genetic algorithm,

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delivers optimal flow adjustments after reintroducing chords of minimal admissible diameters in those lines previously omitted for generating trees. The technique chosen takes up the idea of performing the hydraulic network balance by employing flow correction terms in any loop, the initial flow estimates being associated with random trees.

The genetic variables of TREEGEN were chosen to be the chords as the proper vehicle to improve the topology. FLOWGEN works on improving the flows once the trees have been completed again to reticulation. Given the fact that, once the flows are known, Linear Programming will deliver optimal diameters for a looped system as well, KANET offers the option to run FLOWGEN either independently or based upon the output trees of TREEGEN serving now as input.

Savings of the network costs of 10-20% are guaranteed employing optimization, compared to conventional design methods. This is the common order of magnitude realized by Operations Research methods. The savings may be even higher, in particular, if conventional design methods consist but of diameter estimates supplemented by simulation. Network optimization offers also the advantage of sensitivity analyses quantifying the impact of parameter changes, a valuable information to be utilized for alternative designs and for assessing the data collection.

Once a cost optimal design has been determined, eventually, based upon a design criterion like peak load, it may still be of interest to verify the operation of the system for different demand and future supply patterns. Hence, feedback and communication between and connectivity with *simulation* and *optimization* has been the main objective of KANET.

3 User Interface

It has become state-of-the-art to facilitate working with a complex software package by adding a database and graphics linked to the algorithms, also to guide the user by a manual and a user interface. A summary of KANET's (Fig. 1) User Interface (Fig. 2) will be given. The project management hierarchy consists of three levels. The upper level introduces the overall 'Project', e.g. the name of a city, etc.

On a second level 'Scenario' designates planning & design cases for the same Project. Scenarios may refer to alternative designs in the year 2000, 2010, etc. The graph of the network consisting of nodes and edges (also: links, lines, pipes) stays the same in the same Scenario. The data input is on the Scenario level as well as the choice of the algorithm which may be simulation or optimization.

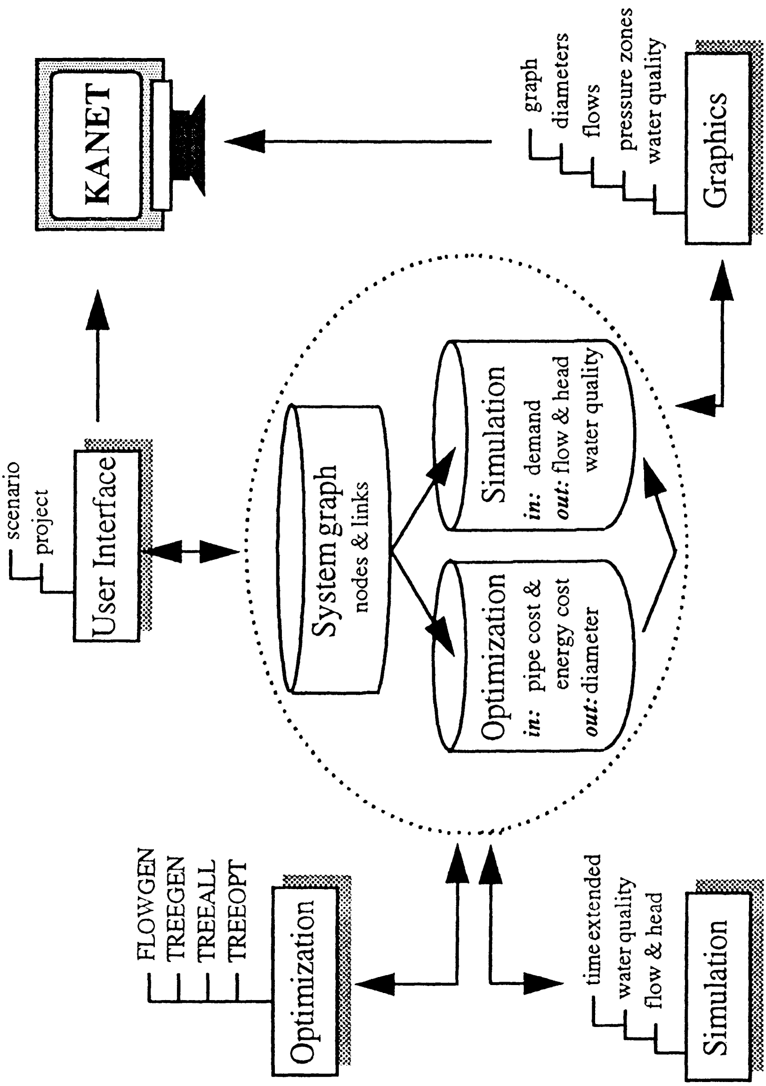

Figure 1: KANET Diagram

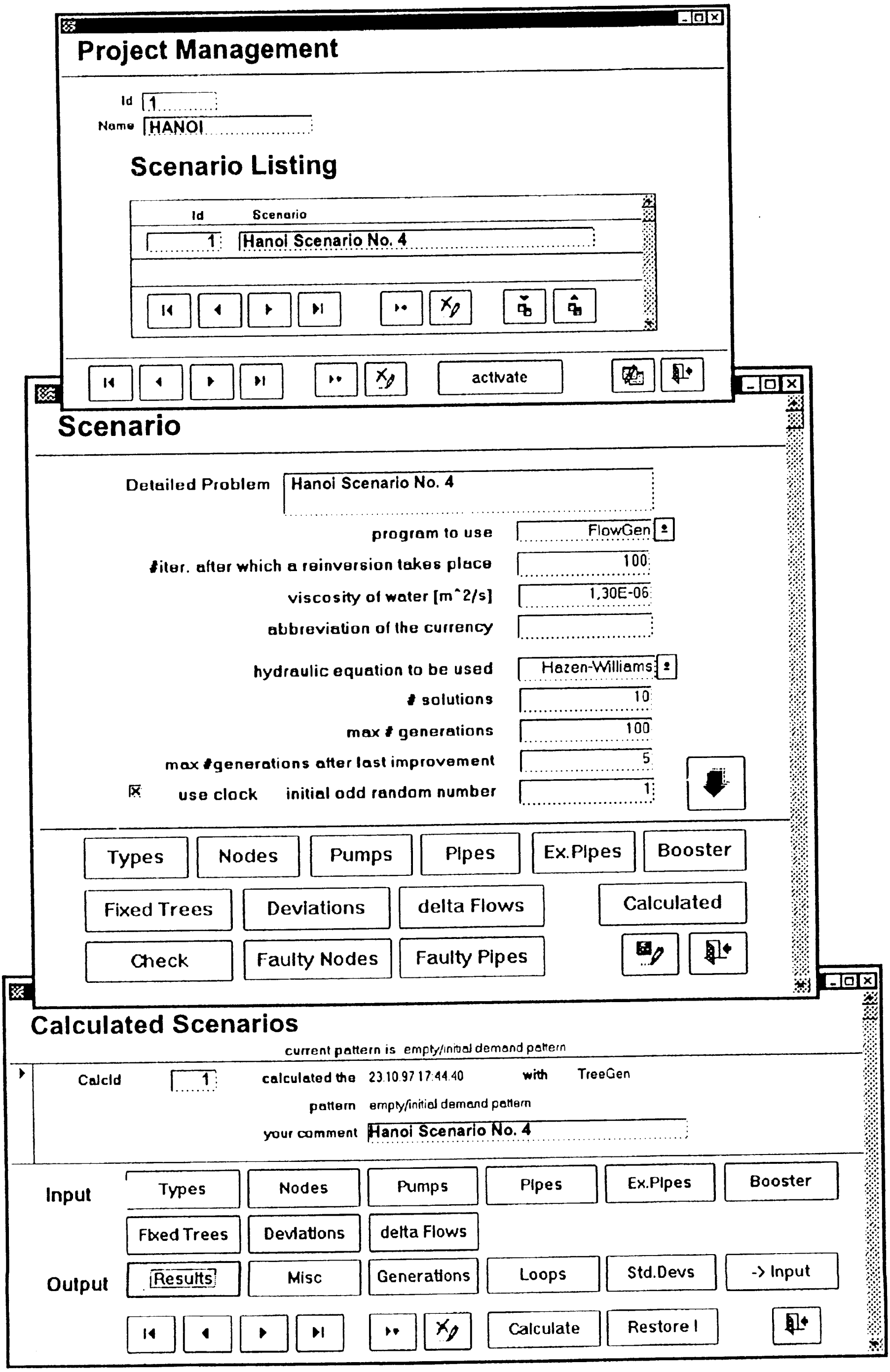

Figure 2: User Interface

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The database makes intensive usage of referential integrity during data input. Renumbering of a node is processed automatically to numerous positions in the database, a link may not obtain upstream and downstream node numbers that have not been defined previously, etc. Internally, there exist 39 tables of data input, 15 tables of data output. If the user wishes to perform calculations after completing the input, he enters the third level activating 'Calculated' in the Scenario window, thus reaching the 'Calculated Scenarios' window menu. Then he pushes 'Calculate'. The calculation delivers output data that are subsequently stored jointly with the input under a calculation ID.

The 'Calculated Scenarios' window offers also buttons to activate data sets of previous calculation runs identified by their respective calculation ID's. Here, the data can be viewed and printed, they cannot be edited and modified. If the data of a previous calculation run are to serve as a basis of a new calculation and are to be edited and modified, the user pushes 'Restore!' in the 'Calculated Scenarios' window. The input data set of the chosen previous calculation will be copied into and overriding the *current input data* set, a file created automatically with a Scenario. Editing of the newly created *current input data* is now possible, except changing the graph since the Scenario is still the same. Input and computational results may be viewed by a graphical system (Fig. 3).

4 Summary

Two separate systems analysis tools are at the disposal of the engineer, in general, to accomplish hydraulic analyses of existing and the design of new networks. They belong to the chapters of *simulation* and *optimization*. The network tool KANET (Fig. 1) introduced here, allows for communication between simulation and optimization by a database in dbase format, also visualizing input and computational results by appropriate graphics (Fig. 3). The engineer, safe from algorithmic and complex data operations, is guided by a user interface (Fig. 2). The simulation provided by KANET is time extended, includes quality propagation as well as numerous hydraulic control devices encountered in practice. The optimization provided by KANET, yielding cost-optimal diameters, uses principles of Operations Research and employs Linear Programming as well as Genetic Algorithms. The presentation is descriptive and not reiterating mathematical formulations given previously. The authors acknowledge the support of the Deutsche Bundesstiftung Umwelt (German Federal Foundation Environment).

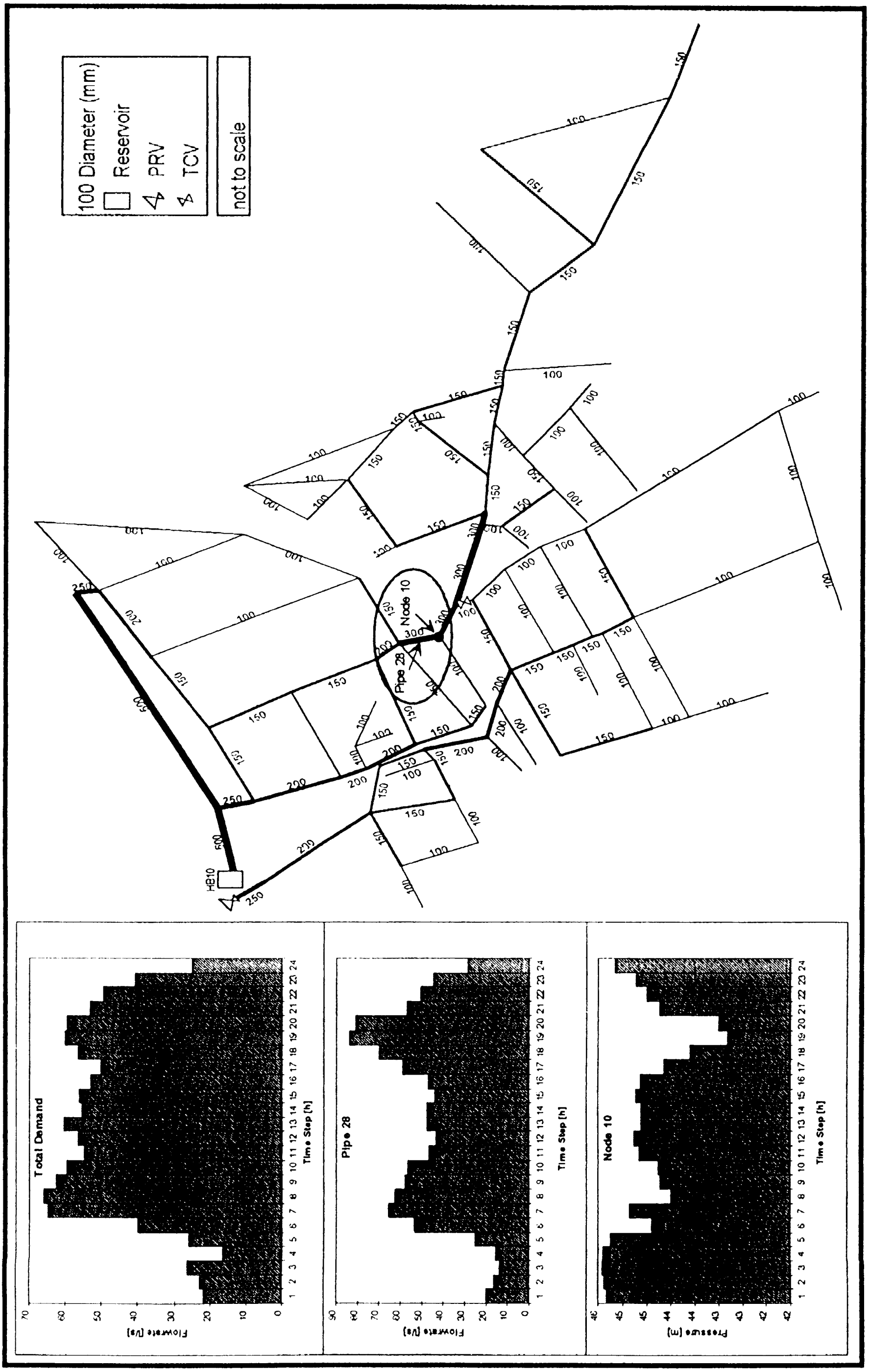

Figure 3: Graphics KANET Erfurt-Marbach

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