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ADAPTIVE MODELING OF WATER SUPPLY NETWORKS FOR IMPROVED PRACTICAL APPLICABILITY OF HYDRAULIC ONLINE-SIMULATION

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Online-Simulation of water distribution networks allows for estimating the current state of the entire network in near real-time. Measurement data coming from sensors at selected positions in the real network are used for driving a mathematical simulation model. Therefore the information gained from the measurements is extended and covers the whole system. As part of online monitoring or decision support systems online-simulations have multiple applications in operations and control of water supply networks.
Although sensors and techniques for data transfer as well as mathematical simulation techniques are highly developed the practical applicability of online-simulations for decision support in large networks still suffers from the high time requirements for the whole cycle of measurement data updates, simulation and post-processing. One common approach to tackle this problem is the aggregation of the underlying models. However, for some applications like contaminant source identification the information that is lost can be crucial for the reliability of the decisions that are made based on the online-simulation results.
In order to enhance online calculations and to improve the practical applicability of large online simulation models an adaptive calculation framework has been developed that allows for running the model with different levels of accuracy but using all one and the same data base. For each problem an adequate level of accuracy is chosen. Higher functions like source identification or optimization algorithms that require a number of extra simulations can be focused on selected regions of the network. For the subnetwork in question detailed data are used whereas the rest of the system is omitted or, if necessary, considered with a lower level of accuracy.
The framework is based on topological analysis and decomposition of the network graph. The paper describes the basic concepts and demonstrates its applicability by means of contaminant source identification.

INTRODUCTION

The decomposition of a general water supply network graph as described in [1] and [2] is a valuable tool for analyzing the topology of the network that in addition allows for enhancing calculation methods of hydraulic systems analysis without losing accuracy. Especially, when the hydraulic simulations and related analysis tools are running online there is a strong need for highly efficient algorithms. In the following section the basics of the method are recapped before its application to the solution of the online source identification problem is demonstrated.

BASIC CONCEPT

Urban water supply networks are complex systems of technical infrastructure. Different parts of the system fulfill different tasks. The pipes can be subdivided into transport, main distribution, distribution and house connection pipes. This sub-categorization of pipes finds its counterpart in the topological representation of the network. A common water supply network graph often consists of a treelike transportation system that connects the different supply areas with the water source. The main distribution system of the supply area includes the most important pipes of the supply areas delivering the water to sub-zones. The distribution network of the supply zones is normally looped in order to ensure the redundancy and reliability of supply in case of pipe bursts or to get enough water to the hydrants in case of a fire. The customers are usually connected to the distribution system by the branched system of end pipes of the distribution network complemented by house connections.

It is common praxis in hydraulic network analysis to simplify the network graph by removing less important pipes and house connections for hydraulic systems analysis. In addition, the nodal demands are often lumped at junction nodes having degree greater than 2. This praxis is sufficient for a number of applications of hydraulic network models. In some cases however it is desirable or even imperatively required to have a model that is more accurate. For that purpose, up to now, the user has to maintain different models for different application since it is impossible to get back from a simplified model to the full pipe model.

To overcome this drawback an adaptive modeling technique is required that allows for moving forward and backward from one level of detail to another. The following concept for decomposition of a general supply infrastructure network graph implements these requirements: In the first step, the different connectivity components of the network graph are identified. A simple breadth first search or depth first search on the augmented network graph (additional virtual links connect a virtual ground node with all kind of source nodes) can be used. Getting more than one connected component means that there exist network parts that have no access to a source and cannot be supplied. After that the components can be subdivided into the core and the forest subgraph. The core consists of looped blocks that are connected by bridges whereas the connectivity analysis of the forest subgraph delivers the trees being the components of the forest subgraph.

All different kind of subgraphs can be further simplified by their topological minor. That means that serial pipes, without bifurcation in the core subgraph, are replaced by a superlink. The topological minor consists of superlinks and supernodes. The supernodes include all the nodes of the original graph with degree > 2. Whereas the set of supernodes represents a real subset of the original set of nodes the incidence relations of the superlinks can be derived from a reordering of the rows and columns in the incidence matrix of the original network graph by use of the following equation:

$$\mathbf{A}_S = \mathbf{A}_{P,C} - \mathbf{A}_{NP,C}\left[\mathbf{A}_{NP,T}\right]^{-1} \qquad (1)$$

$\mathbf{A}_S$ is the incidence matrix of the topological minor (supergraph) and the submatrices on the right hand side refer to the submatrices of the partitioned incidence matrix $\mathbf{A}$ of the original network graph:

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_{P,T} & \mathbf{A}_{NP,T} \\ \mathbf{A}_{P,C} & \mathbf{A}_{NP,C} \end{bmatrix} \tag{2}$$

Since the incidence matrix describes the topology of the network the analytical form of equations (1) and (2) allows for moving forward from a detailed view on the system to a more simplified and backward. For more details on the approach including reordering the reader is referred to [2].

Figure 1 shows different views of graph decomposition on an artificial example network. The original all pipe network shown in Figure 1 a) is first reduced by the forest (Figure 1 b)). The result is the core of the network graph. In Figure 1 c) the topological minor of the core is presented, which is the result of the removal of interior nodes (nodes with degree 2) from the core. The strongest simplification is shown on Figure 1 d) and includes the so-called block graph tree (bgt) of the core.

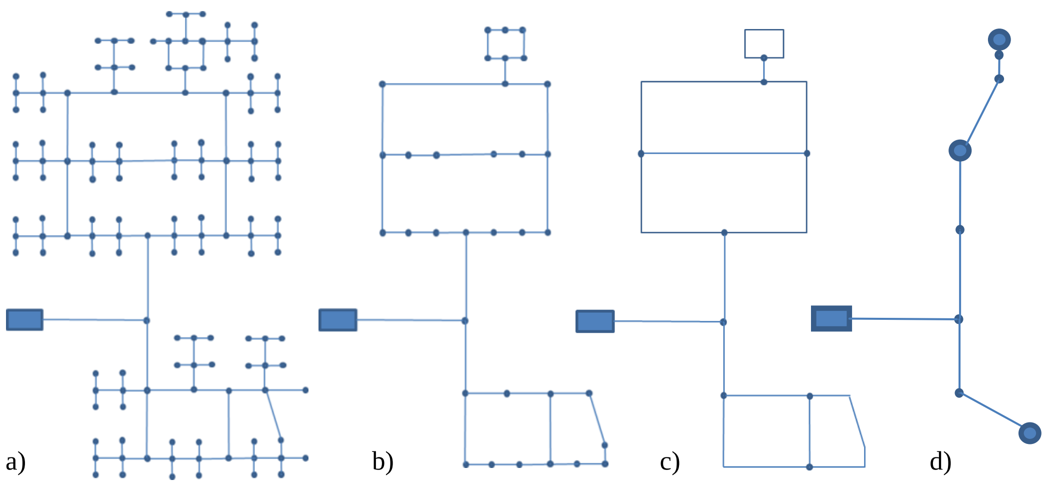


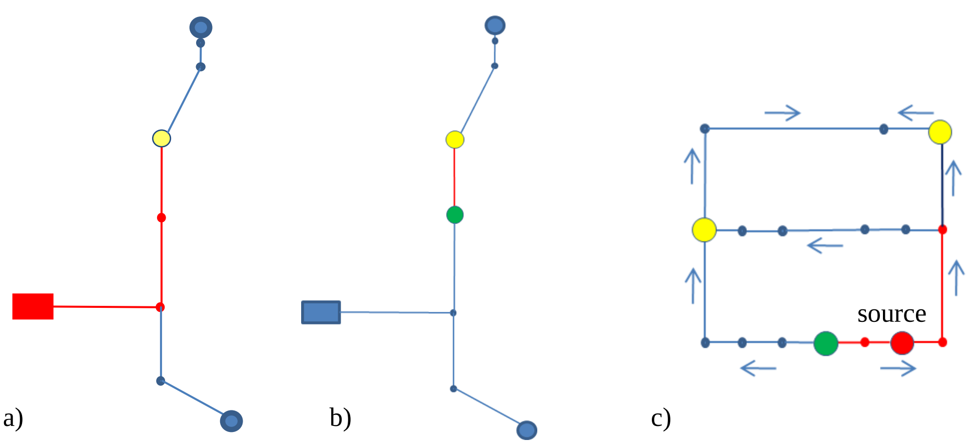
Figure 1: Example for different views on the network graph

It is worth noting here that using a proper implementation the decomposition is fast and can be used online. This is important for consideration of modifications of the network graph by operational changes like closing of valves, pump switches between on and off etc.

Application

Besides enhanced hydraulic simulation and online calculation of subsystems another possible application of the method is the well-known source identification problem. The objective is to identify the possible contamination sources in a distribution network for given water quality sensor alarms. In an online environment the algorithm is started after a sensor alarm has been released. It is natural that the sensor alarms are not all released at the same time but subsequently since the travel time from the source to the particular sensors differs. Therefore the algorithm must be carried out as soon as a new sensor alarm is released. The additional information of the new sensor alarm is combined in the algorithm with the previous ones leading to a decreased number of potential source nodes. Running the algorithm for huge all pipe models is a very challenging task. An approach to tackle this problem is to use the above described decomposition technique. The algorithms are carried out in different stages using for each stage the most appropriate level of detail without loss of accuracy.

The basis of the data that is used for the algorithm is the comprehensive all pipe model of the entire distribution system (see Figure 1 a)). Based on the decomposition of the network the analysis can start with a very rough investigation of the block graph tree followed by more detailed analysis that is carried out for selected parts of the simplified graph. Figure 2 a) shows the analysis of the block graph tree of the example network after an alarm has been released in the block that is represented by the yellow node in the bgt. Using a tree search from the leafs to the root of the bgt the nodes and pipes that are in between the sensor alarm node (yellow node in Figure 2 a)) and the root are possible candidates (red color). If also negative sensor alarms (green node) are considered the area of possible contamination sources can be further decreased (Figure 2b)). Please note that at this stage the yellow node in the bgt only indicates that there are one or more alarms in the looped block that is represented by the block node. In the next step the more detailed model of the block is studied showing the real locations of the positive sensor alarms (Figure 2c)). Assuming perfect sensors it is sufficient to run the source identification algorithm (for example as described in [3], [4], [5], [6]) only for the reduced system of Figure 2 c). The forest is also excluded since, except for massive pumping of contaminated water into the system, the flow direction is from the root to the leaves. As a consequence the pipes and nodes of the forest trees are not possible as sources that can explain the sensor alarms. Figure 2 c shows the state when the contamination has already reached both sensors.



a) b) c)

Conclusion

Besides the presented example there exist a number of different applications that can be derived from the topological decomposition of the network graph and that facilitate execution of almost all kind of algorithms that are used in hydraulic systems analysis. The simplified views, on the one hand, are able to reduce execution time of those algorithms dramatically. On the other hand, they support the understanding of the interactions of the components by simplified views of the system while keeping also the detailed information. Especially in extreme situations this is an essential advantage in contrast to conventional techniques where, either the network is strongly simplified with loss of accuracy, or the running times of the detailed model are too long and it is difficult for the decision maker to keep clarity and to understand the real system behavior.

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