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WDNetXL: hydraulic and topology analysis integration and features

Daniele Laucelli*, Luigi Berardi and Orazio Giustolisi

Politecnico di Bari, via E. Orabona n.4, 70125, Bari, Italy

Abstract

The WDNetXL is an integrated system for water distribution network (WDN) analysis, planning and management distributed as MS-Excel® add-ins. It integrates advanced and robust WDN hydraulic simulation with topological analysis and optimization strategies to support technicians for complex WDN analysis, design and management problems. The paper presents in details the feature of functions devoted to network hydraulic and topology analysis and discusses the technical effectiveness also with respect to planning and management tasks of hydraulic systems.

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Keywords: Advanced hydraulic analysis; Topological analysis; WDNetXL; planning and management of hydraulic systems.

1. Introduction

Nowadays new challenges in water industry concern with the management of existing water distribution networks (WDNs). This is a very complex and multi-aspects activity, in which technicians are asked to provide optimal and reliable solutions that should balance the environmental, financial, social and regulatory aspects. Therefore, in the last three decades the interest for WDN analysis and management is increasing, along with the pervasive development of information technology and increase of computational capabilities, thus leading to a number of achievements of direct interest for water utilities. Some of them are incorporated into commercial or non-commercial software applications, whose core functionality is the WDN hydraulic simulation. However, the research transfer to end users has often been hampered by difficulties of integration of new methods in existing software tools (e.g. EPANET2), which can imply the modification of procedures for implementation of input data and network analysis. The hydraulic engineers and technicians are actually often unwilling to give up old (familiar) tools and

* Corresponding author. Tel.: +39 080 5963726
E-mail address: danielebiagio.laucelli@poliba.it

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methodologies for new (but more complex) tools, although more effective. These conditions have made the research transfer still far from be complete, making advances of research less useful for applications to real scale.

In this scenario, the authors recently proposed a new software tool called WDNetXL [1], which aims to integrate different analysis tools developed and tested as part of their research activities into a single framework within a worldwide used software environment, like MS-Excel®. The WDNetXL is an integrated software framework composed by several MS-Excel® add-ins for WDN analysis, planning and management, which combines advanced and robust WDN hydraulic simulation with topological analysis and optimization strategies to support technicians for complex WDN analysis, design and management problems. The WDNetXL system allows accomplishing just-in-time technology transfer from technical research to WDN management sector through a holistic platform, ready for possible extensions to the latest innovations, thus providing an upgradable support to match current and future technical needs. This provides also a practical tool for training of engineers ranging from university classes to continuing education at water companies. Its versatility also makes the system suitable to implementation of customized solutions through a virtuous cycle among users, researchers and developers. The WDNetXL system is "open source" in the sense that, although the dynamic link libraries (DLLs) are binary files, it is possible to use them beyond the templates provided in the original package, for example linking them to a GIS or other systems by means of standard programming languages that connect MS-Excel to external applications. One of the main ingredients is the hydraulic simulation, which is almost advanced, if compared to EPANET2 [2], in terms of robustness, hydraulic consistency and flexibility in analyzing many WDN elements like components of water demand, leakages, control devices, etc.

The paper presents those functionalities concerning WDN analysis and discusses the technical effectiveness with respect to planning and management tasks of hydraulic systems:

- Steady State Hydraulic Analysis (single snapshot of the system behavior encompassing analysis tank filling/emptying process, background leakages from pipes, pressure/flow control devices, etc.);
- Extended period Hydraulic Analysis (sequence of snapshots varying states of device, water demands, reservoir/tank levels, pump working conditions, etc.);
- Steady State Hydraulic Analysis considering topological changes due to isolation valve shutdowns for planned or unplanned works in the network;
- Extended period Hydraulic Analysis considering a sequence of snapshots under topological changes due to isolation valve shutdowns for planned or unplanned works in the network.

2. WDN Analysis

The effectiveness of the different actions/operations that can be performed on an existing WDN (rehabilitation, expansion, districtualisation, calibration, etc.) requires accurate and detailed hydraulic and topological analysis. In particular, an accurate network analysis procedure must integrate the simulation of hydraulic networks, identify the key elements of the network (for example, valves and districts) and detect topology changes resulting from abnormal operating scenarios. WDNetXL is able to support these activities by means of a dedicated module that collects a suite of functions (MS-Excel add-ins) for the specific aspects of WDN analysis. Fig. 1 shows the user interface of such WDNetXL module.

All analysis functions in WDNetXL system share the same network hydraulic simulation model, which can perform the classic demand-driven analysis of WDN, as in EPANET2 [2][3], or the pressure-driven analysis of WDN by means of a more recent approach integrated by a pressure-driven background leakage model [4]. The key features of WDNetXL system concerning directly the hydraulic simulation model will be discussed in the following, along with related scientific works (only few for the sake of brevity), and in comparison to the most worldwide used hydraulic simulation software EPANET2.

The effectiveness of network analysis also depends on easy handling and visualization of data and results. About this, WDNetXL is equipped with a 3D network visualization module that allows editing individual WDN element features, visualizing simulation results, detecting current WDN topology. In particular, as detailed later on in the text, it is possible to identify the network segments based on isolation valves, which is not allowed in EPANET2, which cannot account for network districtualisation.

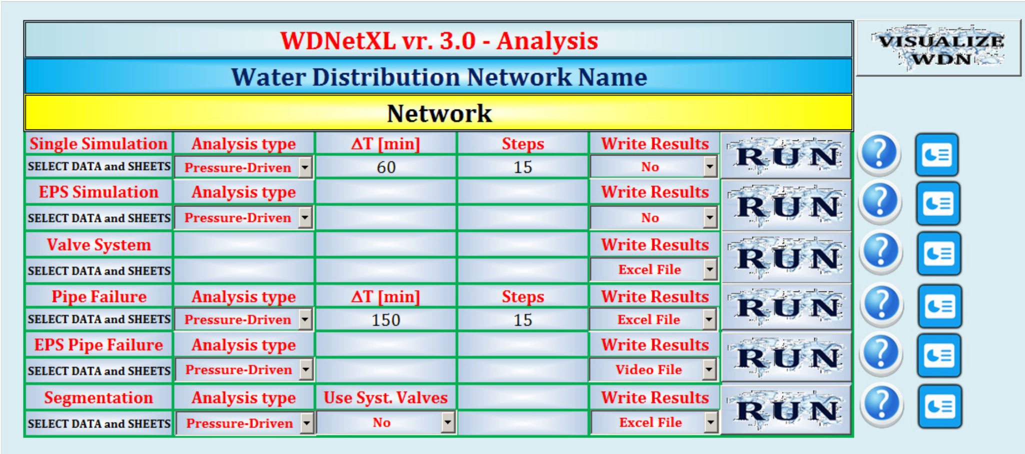

Fig. 1. User interface of WDNetXL analysis module.

Additionally, data management in MS-Excel permits to manipulate easily input data having a basic knowledge of MS-Excel. While working on a hydraulic model, users can have direct access to data (stored as MS-Excel spreadsheets) and use any MS-Excel function/feature (e.g. filters; graphs, texts, link to external documents, etc.) to analyze, elaborate, comment, etc.. Results of analyses are returned as MS-Excel spreadsheets, thus permitting full customization by exploiting the interoperability with MS-Office modules (text editing, presentations, etc.).

2.1. Topological Analysis

Topological analysis is very important for different tasks in WDN management. In real networks, the state of the isolation valve system (IVS) can influence the actual topology (i.e., connectivity with respect to sources of water) of a WDN, thus the analysis of network segments (i.e., subset of network elements) due to the existing IVS can be crucial in identifying current and/or potential problems.

WDNetXL can help the user in studying the existing IVS of the WDN. The IVS is analyzed using the algorithm described in [5][6], which is based on the use of topological matrices for the network model. It allows a subset of isolation valves to relate to each network segment (composed of pipes, nodes, pumps, etc.). Each valve works to isolate two network segments or zero if it is non-useful [6].

Analysis of current WDN topology is fully integrated with the hydraulic solver module in WDNetXL. This permit to simulate the effects of WDN topology alterations that happen within the same simulation time step (see Fig. 2). Please note, in the left-upper corner of Fig. 2, the visualization of the network segments produced by WDNetXL, where the segments are highlighted in different colors. Conversely, analysis of current WDN topology needs to be performed outside the EPANET2 hydraulic solver module, and this requires numerical expedients to simulate the closure of automatic control valves within the same steady state simulation.

The solution of the hydraulic simulation problem in WDNetXL is an enhanced version of the Global Gradient Algorithm (GGA) [3] used by EPANET2, known as EGGA [7]. The algorithm EGGA can simplify the topology of the network, not considering (removing) serial nodes and pipes along with the solution of the system of nonlinear equations, thus obtaining higher computing performance than the GGA. This is particularly true for real large networks, when connections to private households are included in the topology of the network.

For example, on a very large network (up to 160,000 nodes) it has been proved robust and fast allowing an average time for each run lower than 0.5 sec [8]. This feature involves a considerable computational advantage for all analyzes that need a network simulation for hundreds or thousands of times (for example, the multi-objective design, calibration, reliability analysis based on a statistical approach, etc.).

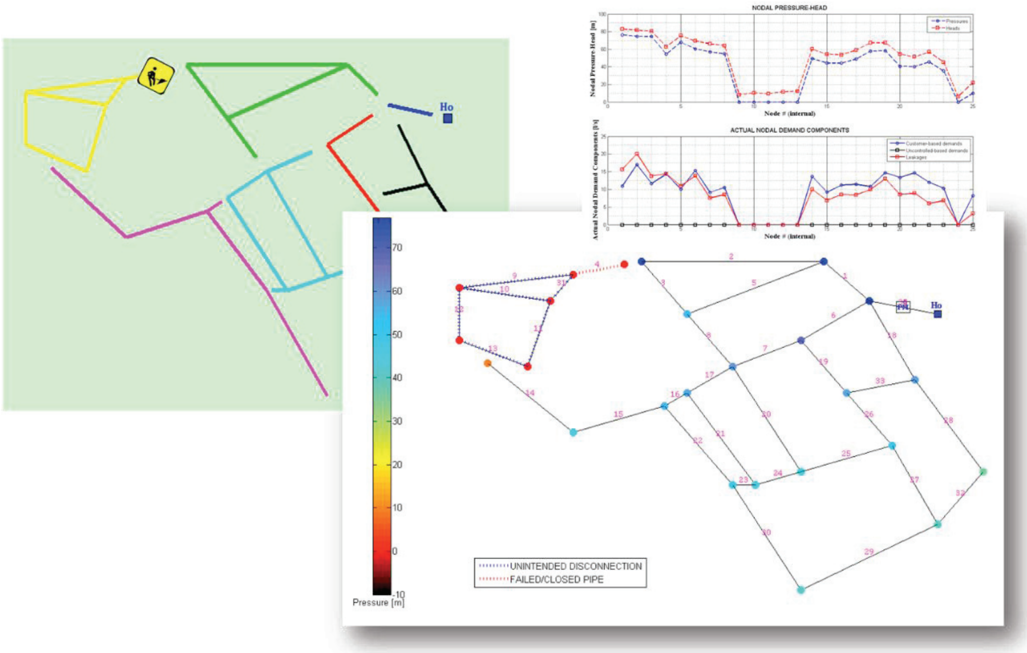

Fig. 2. WDNetXL can simulate the effects of WDN topology alterations in the same simulation time step.

2.2. Steady-state hydraulic analysis

In WDNetXL, the steady-state simulation of a water network (snapshot) relates to a particular period of the day, which duration is defined by the user (for example, greater than or less than 60 minutes). During this period, the steadiness of the boundary conditions are assumed as valid. The hydraulic connectivity of the network before and during the simulation are automatically detected, as above described [5], for example identifying the status of the check valves, pumps and gate valves [9]. In particular, robust simulation of directional devices (e.g. Check Valves – CHV - and Flow Control Valves – FCV) in WDNetXL is based on the adjustment of minor loss coefficient of valves outside the solving algorithm, and is integrated with the analysis of topology. This avoids the expedients used in EPANET2 that are known to lead to non-convergence or incorrect solutions [10][11]. Actually, the simulation of directional devices in EPANET2 checks for all constraints simultaneously after each second iteration and modifies the system in points in which the constraints are violated. Therefore, the simulation algorithm in WDNetXL is sensitive to changes in network topology, being able to reproduce the actual variations in the network [6].

One of the most important feature of the hydraulic simulation module in WDNetXL is the possibility to perform the pressure-driven analysis of the WDN, thus including the simulation of background leakages, and the definition of several components of the demand in each node [12]. In particular, background leakages are modelled at node level (e.g. simulating pipe bursts dependent on nodal pressure, leading to large outflow but low total water volume lost because usually reported) and at pipe level (e.g. background leakages dependent on average pressure along pipes, leading to lower flow than pipe bursts but higher total volume of water lost because usually unreported). This difference permits to simulate the effects of pressure management on different leakage components, being this feature very important for preparing plans for leakage control and the related evaluation of their economic feasibility. Leakage coefficients and exponents for each nodes can be set according to the FAVAD concept and Germanopoulos formulation of background leakages [4], as exemplified in Fig. 3, showing that in real WDN, background leakages are spread over the entire network (also close to customers connections); in the WDNetXL hydraulic simulation model they are represented as uniformly distributed background leakages along pipes used in the WDN model, according to the Germanopoulos formulation.

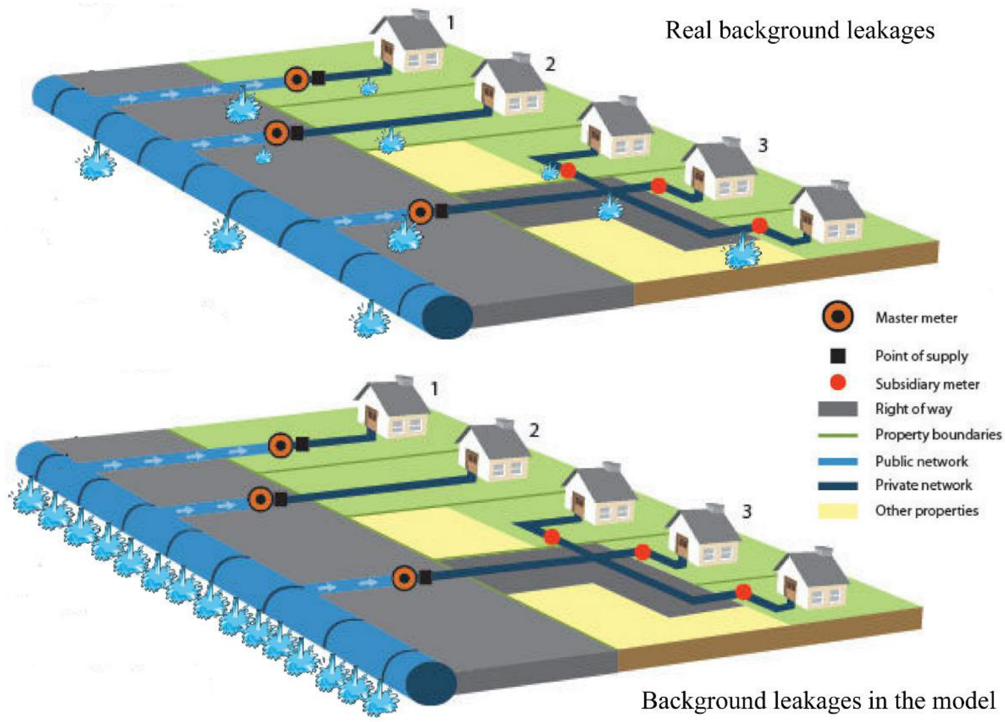

Fig. 3. Background leakages representation in WDNetXL: the real background leakages in the WDN (upper figure) are represented as uniformly distributed background leakages along pipes in the WDN model, according to the Germanopoulos formulation.

In EPANET2, leakages are usually modelled using the emitter components, thus as a pressure-driven component over and above the water consumption associated with each node in the network, which conversely is modeled as demand-driven. This lead to some problems that are still to be fixed [13].

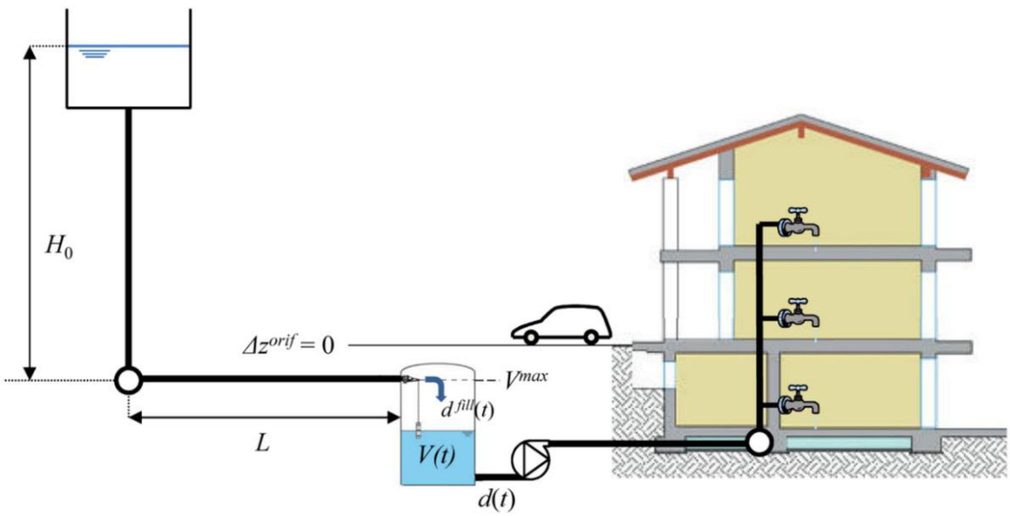

Fig. 4. Private local storage scheme assumed in the WDNetXL hydraulic simulation.

Finally, two innovative features of WDNetXL, that are not implemented in EPANET2, are the pressure-driven simulation of water demand delivered to buildings with multiple floors and the simulation of water supply through private water storages (e.g. roof/basement tanks) at each node (see Fig. 4) [14]. Since different delivering conditions can influence the actual levels of service, it is important to include such features in complex networks analysis, in order to have a more realistic picture of possible scenarios, and consequently allocate investment for enhancing the water delivery service.

2.3. Extended period hydraulic analysis

Extended period simulation (EPS) of a WDN inherits all the analysis features of single steady-state simulation although it is a sequence of snap-shots of the hydraulic system. EPS further requires additional data, such as for example demand patterns, which are easily implemented as MS-Excel tables.

It is worth mentioning that the hydraulic solver module implemented in WDNetXL is a Generalized GGA (G-GGA) [15], which enables the analysis of varying tank levels both in the single snapshot and in EPS without using the Euler method [16]. WDNetXL is able to simulate variable level tanks in the same steady state simulation step by coupling mass and energy balance equations. This permits to overcome the known instabilities of EPANET2 solver in tank simulation and some problems in overall mass balance in the network, see Fig. 5. In fact, EPANET2 performs the simulation of variable level tanks by uncoupling mass balance and energy balance equations, thus requiring multiple steady state simulation steps [15][16]. Moreover, in WDNetXL, thanks to the G-GGA solver, reservoirs are treated as a special case of tanks and in tank nodes the mass balance components of pressure-driven analysis are accounted, as well as fixed external supplies, if any.

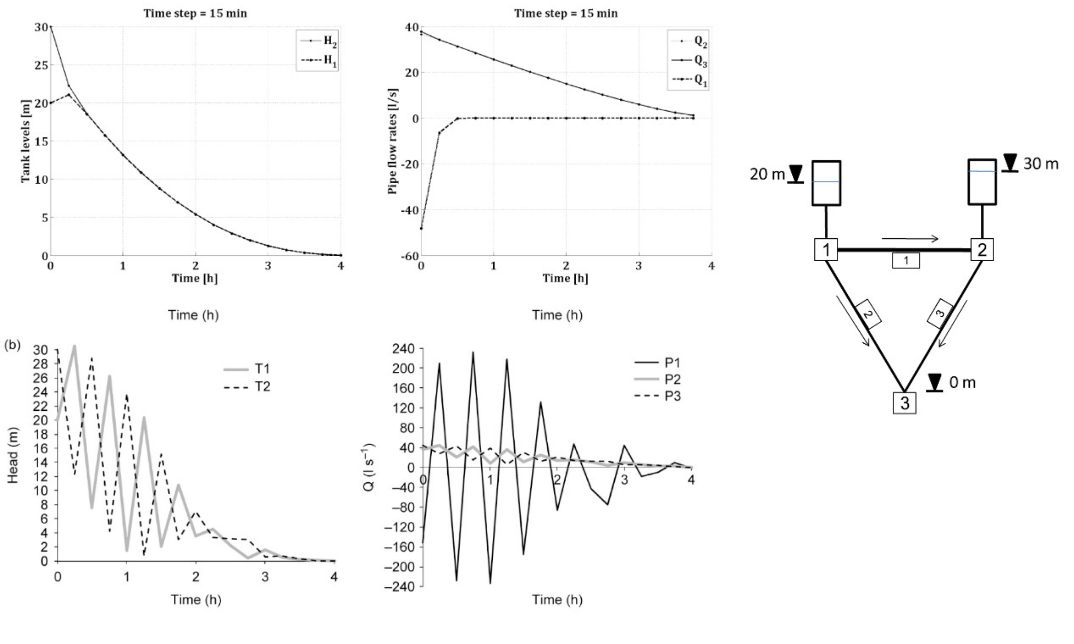

Fig. 5. (Scheme on the left) Two emptying interconnected tanks starting at time zero with different water levels (from [16]); diagrams of tank levels and flow rate in the three pipes of the scheme returned by WDNnetXL (a) and EPANET2 (b) (from [16]).

Among devices that can vary their status/behavior along with the EPS, the most important to be considered in many planning and management tasks of hydraulic systems are the pressure control valves (PCVs). They are largely used for pressure control in order to limit water loss from existing WDN, and therefore their accurate simulation within the network analysis is of crucial importance. EPANET2 permits to implement PCVs only controlled by upstream/downstream node of the valve link. Therefore, control of pressure over time can be performed by modulating the setting point of PCV over the operational cycle to keep a desired pressure value in the zone under control. This requires accurate definition of demand patterns as well as accurate model calibration in order to have reliable simulation of pressure downstream the valve. Conversely, WDNetXL allows the simulation of PCVs controlled also by remote set points. This means that the desired pressure value at remote controlled node can be set based on required service pressure (possibly variable over time), having the advantage that the search for patterns of pressure set points is no longer based on the extended period simulation (i.e. on accurate definition of demand patterns and model parameters). In fact, the pressure at critical node is influenced by the water requests into the networks, which changes over time and spatially (see Fig. 6). WDNetXL easily allows the design and verification of the remote (critical) set points. It is also possible in WDNetXL to define a set point value varying over time. This makes WDNetXL analysis and optimization functions ready to simulate the effects of using ICT strategies for real time control by programmable logic controller (PLC) actuated valves based on remote acquisition and transmission of nodal data.

Additionally, the analysis of the area of influence of control devices (e.g. PCV) is supported by the water trace analysis available in another integrated module of WDNetXL. This allows studying the actual controllability of some nodes by some candidate locations of PCV/variable speed pumps (VSP) and the preliminary selection of the most effective set point of pressure control devices. Conversely, the locations of time-modulated PCVs need to be pre-specified in EPANET2, then being able to analyze a limited number of possible control scenarios.

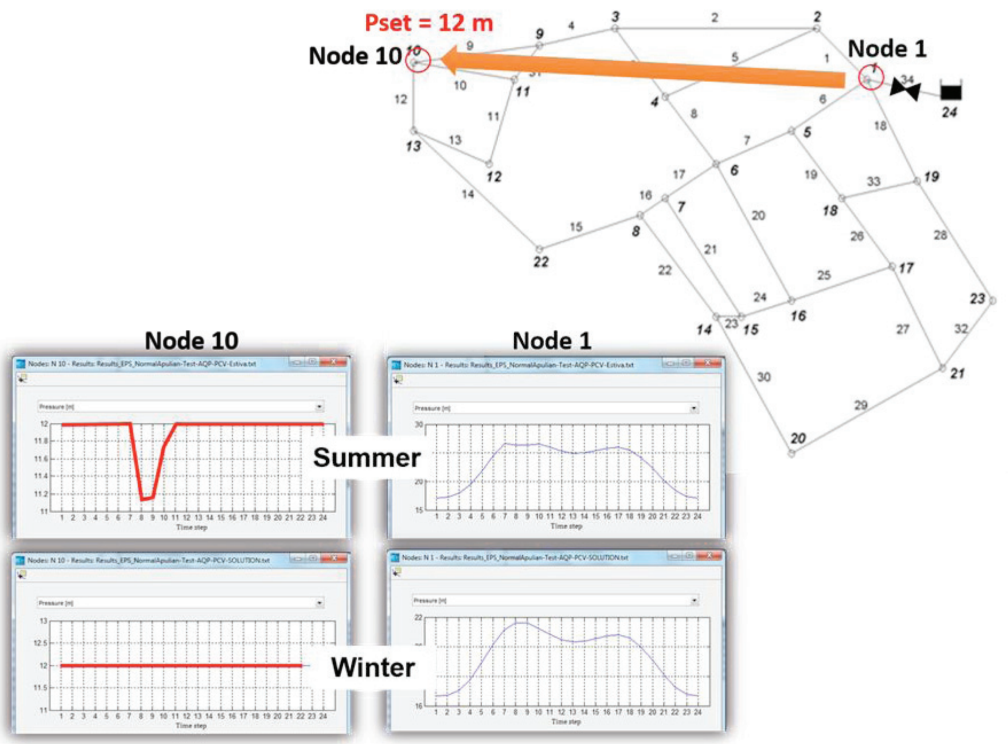

Fig. 6. Example of PCV (on pipe 34) controlled by pressure at node 10 at maximum (summer) and minimum (winter) demand scenarios. Note that when pressure at node 10 drops (at peak summer demand hour) the PCV is fully open, while in the winter scenario the PCV modulate pressure to actually match demand pattern.

EPANET2 permits to simulate VSP only by assigning the speed factor patterns, but not based on pressure reading during the EPS. WDNetXL can define specific time patters for VSP and can simulate VSP controlled by remote set point is available. This permits to simulate pumps with inverter controlled by remote set points.

Finally, WDNetXL returns a number of tables and diagrams produced as results for each time steps considered, allowing the user to evaluate the behavior of the network over an extended period, e.g. examining the impact of water loss, or the functionality of a pressure-reducing valves, etc..

3. Analyzing pipe failure scenarios: Steady-state and EPS simulation

Unlike many similar tools, WDNetXL allows the user to perform a WDN hydraulic simulation (snapshot and extended period) accounting for one (or more) possible scenario(s) of element failures (e.g., pipes, nodes, etc.). Therefore, for single pipe isolation, pipe segments in the network (generated by the IVS) are taken into account. The association between IVS and pipe segments are automatically performed and the connected WDN topology are consequently detected assuming the valve closures for pipe repair, including segments unintentionally intercepted (i.e., unintended isolations) [6]. All features of hydraulic simulation as above described can be included in the pipe failure analysis, thus allowing understanding all possible consequences of failure(s) on several devices in the WDN (e.g., tank levels, pressure settings, pressures, customers' demands, etc.).

This could be performed automatically by including any combination of breakages/interruptions of elements in the WDN, since the possible failure scenarios are implemented as simple Excel tables; in addition, the user can employ any pipe failure model to produce the failure scenario. The results are given in tables, diagrams and as network topology plots (after modifications due to pipe failures, see Fig. 2) that allows the user to have a clear picture of what happens in the WDN with the existing isolation valves system when pipe failures occur.

3.1. Example application

A small application is reported here to show the potentiality of WDNetXL in analyzing a WDN under failure scenarios. The analyzed network is Apulian Network, which is widely used in the literature as benchmark network in several applications [8]. In this particular case, the network has a pressure surplus that leads to an average daily leakage rate of about 35%. Fig. 7 (on the left) shows the diagram of daily volumes of the different demand components evaluated by the EPS function in WDNetXL (i.e., 24 hours). As reported in the legend in the upper right corner, the analyses include only the customers' demand and the background leakage, evaluated in a pressure-driven analysis as above described.

Then, the water utility decide to introduce a PCV on the pipe leaving the reservoir controlling a critical (remote) node in the network (node n. 10, see Fig. 8) in order to control pressure and reduce leakages. This leads to an average daily leakage rate of about 18%, as arguable from the diagram in Fig. 7 that shows (on the right) the new diagram of daily volumes of the different demand components. Moreover, Fig. 8 (on the right) shows the network layout with a color ramp indicating the rate of pressure deficit (as percentage) for each node over the 24 hours analyzed; on the left side of Fig. 8 there is the pressure set (equal to 10 m) behavior over the analyzed day. In this layout, the label "Pset" indicates the controlled node, and "PV" indicate the location of the PCV.

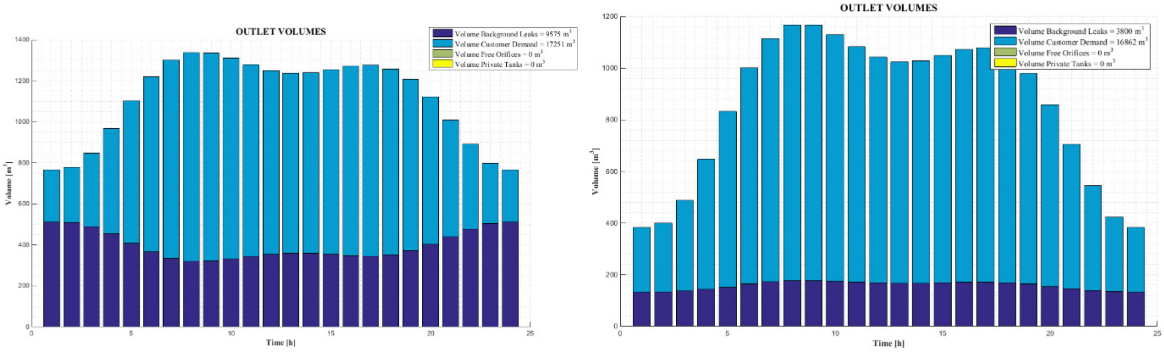

Fig. 7. Diagram of daily volumes of the different demand components before (left) and after (right) the installation of a PCV.

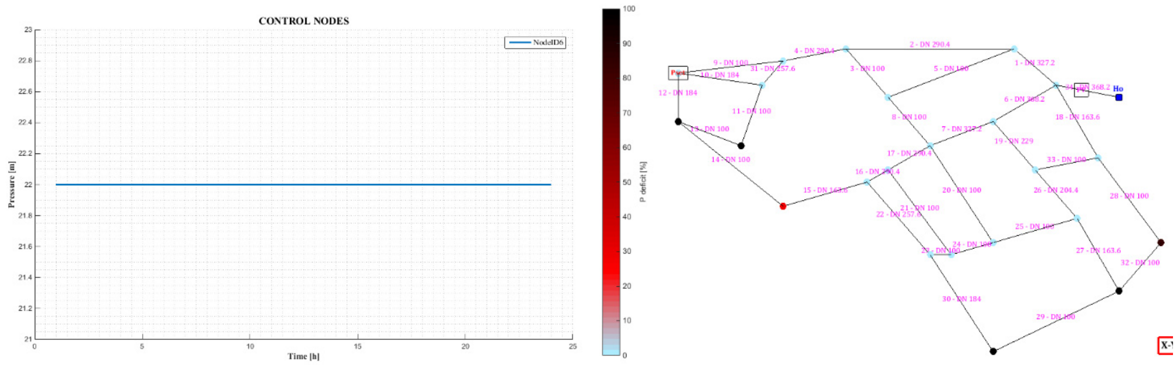

Fig. 8. Network layout with rates of pressure deficit (as percentage) for each node over the 24 hours analyzed; on the left side, there is the pressure set behavior over the analyzed day.

Finally, in case of some planned repair works in the network, the water utility can analyze the possible consequences through the EPS failure function in WDNetXL (over the 24 hours). Pipe number 5 (see the red dotted lines in Fig. 9 – left side) is assumed to be repaired, and thus, according the existing IVS, the whole segment (the blue dotted lines in Fig. 9 – left side) has been recognized and removed by WDNetXL from the network topology for the analysis. Note on the left side of Fig. 9 that, as for each hydraulic analysis in WDNetXL, the network layout is accompanied by a color ramp indicating the pressure head in each node of the network. This immediately shows to the analyst which part of the network can suffer of pressure deficit and which not.

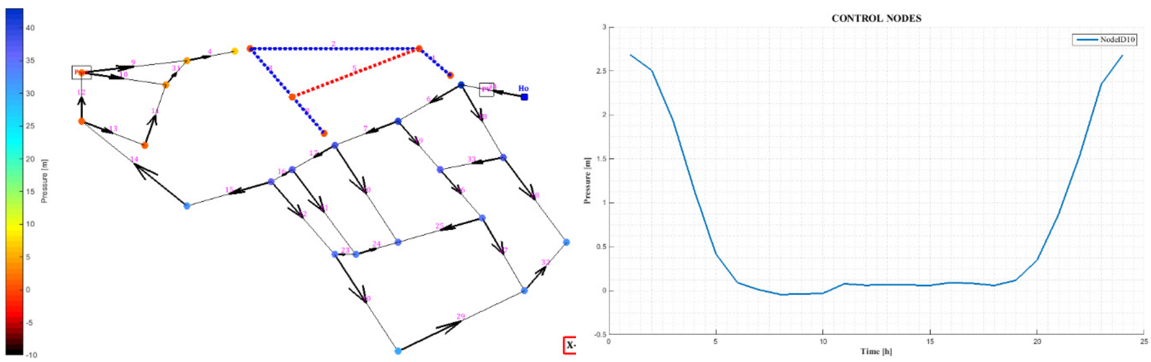

Fig. 9. Network layout with removed segment and pressures at 10 am (left); pressure set behavior over the analyzed day with failure (right).

WDNetXL also returns for each analyzed hours diagrams showing the actual available nodal pressure and consequent delivered demand and possible leakages (see Fig. 2, for example), from which is possible to quantify the pressure deficits during the repair period, thus helping the water utility in preparing a mitigation plan and assess alternative strategies. In particular, it is also possible to study the behavior of the network in case of alternative locations of the PCV. For example, in the analyzed failure scenario, if the PCV was controlling the downstream node of the pipe where it is installed (node 1), as only possible in EPANET2, it should be still working without regards the actual demand pattern caused by the repair works (see, for the sake of brevity, the color of node in the layout on the right side of Fig. 9, indicating a pressure head of about 40 m).

Conclusions

The paper presents the main features and functionalities of WDNetXL system [1], for advanced WDN hydraulic analysis. WDNetXL implements different analysis tools developed and tested by the authors in a number of research studies. The WDNetXL package is in continuous evolution, pursuing the mission to transfer up-to-date research achievements to users in an effective way. Once a method/technique is progressively improved/developed and tested, it can be directly applied to all the WDNetXL functions, as they are built in the same data framework.

In this particular paper, the considered and discussed key element of WDNetXL is the hydraulic simulation model, which is quite advanced if compared to EPANET2, in terms of robustness, hydraulic consistency and flexibility, which is integrated with an advanced and innovative WDN topological analysis tool, permitting to perform a wide range of analysis for existing and new WDNs.

The advanced and robust WDN hydraulic simulation with topological analysis is integrated within the WDNetXL system, thus they can be exploited for all the possible problems that WDNetXL can tackle to support technicians for complex WDN analysis, design and management problems.

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