Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 70 (2014) 152 – 161

Procedia Engineering

www.elsevier.com/locate/procedia

12th International Conference on Computing and Control for the Water Industry, CCWI2013

Energy saving and leakage control in Water Distribution Networks: a joint research project between Italy and China

L. Berardi[a]*, S. Liu[b], D. Laucelli[a], S. Xu[c], P. Xu[c], W. Zeng[d], O. Giustolisi[a]

[a]Technical University of Bari, via E. Orabona 4, Bari 70125, Italy
[b]Tsinghua University, School of Environment, Beijing,China
[c]Beijing Tsinghua Tongheng Research Institute, Beijing, China
[d]Jiangsu Jiangnan Water Group, Wuxi, China

Abstract

One of the most challenging problems in the Chinese water sector is to fulfill water requests in urban areas with increasing population density and deteriorate water distribution infrastructures. Effective decision support systems (DSS) are required to manage energy consumption for pumping by simultaneously controlling leakage volumes. A recently approved joint project between Italy and China aims at transferring the latest advancements on water distribution network (WDN) analysis and management to Chinese water engineers to develop effective DSS by using the WDNetXL system (www.hydroinformatics.it). The preliminary DMAs design on a pilot WDN is reported to exemplify the WDNetXL decision support paradigm.

Selection and peer-review under responsibility of the CCWI2013 Committee

Keywords: Water distribution system modeling; Local water storages; Presssure-driven simulation; Extended period simulation

1. Introduction

Running a WDN requires energy for treating water and pumping it through the pipelines in order to satisfy customers' requests with sufficient pressure. Unfortunately, in highly deteriorated WDN, water leakages associated with the required minimum pressure regimes often result into severe water wastage, customers' dissatisfaction and non-revenue water (NRW). Such a management problem is further exacerbated in the Chinese context due to the

*Corresponding author. Tel.: +39-080-5963726; fax: +39-080-5963726.
E-mail address: l.berardi@poliba.it

Selection and peer-review under responsibility of the CCWI2013 Committee
doi:10.1016/j.proeng.2014.02.018

complex and rapidly changing urban areas where the increasing population density is putting pressure on existing water distribution infrastructures.

In the past decades, Chinese water utilities have attempted to reduce the NRW by implementing several technologies and management strategies. Nonetheless, the cost-effectiveness of such campaigns has always been questioned due to the scarce results achieved.

Actually, there are some major limitations of the Chinese water sector which are recognized to hamper effective WDN management practices and are ascribed to the lack of professional training of the engineers in water utilities and the absence of structured decision making processes.

In January 2013 the project titled “Energy saving and leakage control in water distribution networks: development of a decision support system” has been included among the significant research projects eligible for funding within the framework of the “Agreement on Scientific and Technological Cooperation” between Italian Government and Chinese Government.

The project pursues two main objectives aimed at overcoming the abovementioned major limitations: to train Chinese water technicians in developing decision support systems (DSS) for sustainable management of WDN; to develop and implement a customized DSS for a real Chinese pilot WDNs, which may provide practical guidelines for large scale applications.

The technology transfer and the training of technicians will be achieved by using the WDNetXL system (Giustolisi et al., 2011, www.hydroinformatics.it) which is a recently developed system that integrates the internationally most advanced methodologies in WDN analysis and management into functions working in Microsoft Office Excel (MS-Excel) environment. The ease of use of WDNetXL and the possibility of customizing its functionalities permit to device dedicated DSS by using all information available to water utilities and incorporating peculiar management needs.

2. Project motivations and objectives

In China, the average NRW rate is about 20%; in northern China, the NRW is even higher up to 40% (due to the melting process of ice during the spring which could lead to the uneven settlement of soil and might result in pipe leaks). In addition, the increased water requests in urban areas results into progressively increasing energy consumption for treating and pumping larger and larger water volumes. These circumstances have put great pressure on the managers of water utilities in order to reduce the NRW and implement efficient energy consumption strategies.

Unfortunately, the technologies and management practices implemented in the last years did not result into significant reduction of NRW and water companies appears to be not prepared in coping with optimal energy management problems. Although there are several reasons for this, three main aspects are recognized to entail possible areas of improvement: (a) lack of available data, (b) lack of a structured decision making process and (c) lack of professional training for the engineers in water utilities.

(a) Data availability is a big issue in many water utilities. Although some water utilities have GIS format pipe data, the accuracy is not always satisfied and some data are missing. In addition, the lack of efficient decision support systems, that might exploit detailed information on the WDN, further reduces the motivation for improving the accuracy of data collection.

(b) The decision making process is always “experience oriented” and, only in some cases, attempted to apply international guidelines to the peculiar Chinese context. Nonetheless, most of existing studies have been developed on urban areas (i.e. in Europe or in the U.S.A.) showing very different conditions from China. One example of this is the configuration of DMAs which are aimed at monitoring flow and pressure through the network, mainly for leakage control purposes. Many researchers have indicated that a DMA should cover 3000-5000 households (e.g. Farley and Trow, 2003). However, in the case of China, where skyscrapers are commonly built for resident purpose in recent years due to high population density, 3000-5000 households mean just about 10 buildings. This have confused the decision makers since applying such criterion would result into huge number of DMAs, thus impairing their effectiveness for supporting leakage control.

(c) The professional training of the engineers in water utilities is only delegated to services provided by software vendors. Indeed, in the water software market, there are several emerging software applications which have the capability of hydraulic analyses and providing support to decision making. However, it is quite rare that the local water engineers fully utilize such functions due to lack of professional knowledge in operating such software. In addition, these applications are not flexible enough to incorporate the latest advancements on WDN analysis and to develop customized decision support tools (i.e. reflecting the Chinese context). This reduces the motivations for their use by technicians.

On this premise the cooperation project between Italy and China, is primarily aimed at transferring to the Chinese water sector the most advanced systems to support optimal decision-making in such a complex WDN management scenario. While doing so two objectives will be contemporarily pursued:

1) the training of water engineers in the analysis of WDN and the development of effective decision support systems (DSS);

2) the application of the analyses procedures and DSS on a real Chinese pilot network, in order to immediately test their effectiveness and promote large scale applications.

The simultaneous realization of such objectives during the project will be achieved by following three main phases, aimed at developing a common technical-scientific framework between the two international teams and, next, to produce decision support tools of practical effectiveness for the Chinese water sector.

In the first phase all participants will share the information on relevant expertise area in order to integrate knowledge. On the one hand, the Italian research team (constituted by the developers of the WDNetXL system), will train Chinese water technicians on using WDNetXL, in order to make them familiar with both system architecture and its potentialities for next developments. On the other hand, the technicians from Chinese water sector will examine the current WDN management practices, in order to point out its peculiarities and criticalities to be considered in the successive project steps. During this phase, some of the decision support functionalities already available in the WDNetXL will be applied on real Chinese water distribution networks, as exemplified in the following of this paper.

In the second phase, the methodology to develop a DSS for effective, efficient and sustainable WDN management will be studied and implemented into the WDNetXL system. A leakage monitoring system will be setup in the pilot network and data collected will be used to develop an accurate hydraulic model. Thereafter, the architecture of the DSS will be developed by defining the technical criteria to be matched during the search for optimal management strategies, by exploiting the experience of Chinese technicians, field data and intermediate results obtained by applying WDNetXL functionalities on the pilot network.

The third phase is conceived to implement the new DSS into the WDNetXL system and training other technicians from water utilities on using the advanced tools. This phase is assumed to be the first step for next wide application of project results in terms of advanced methodologies and DSS. In fact, the integration of existing expertise within a structured decision support framework is of primary importance to improve the adaptability of WDN management to cope with rapidly changing conditions.

Moreover, during this last phase, students from Chinese university will be also trained on developing decision support systems for WDN analysis and management, based on WDNetXL system. This action is supposed to increase the awareness of future engineers about current potentialities in managing WDN to be applied on Chinese water sector in the near future.

3. Research transfer paradigm of WDNetXL system

In recent years, due to the progressively increasing advances in data harvesting (e.g. even based on GIS) and computational capabilities, many software houses worldwide have produced technical applications which have the capability of classical hydraulic analyses. At the same time, a number of researchers have developed procedures and tools aimed at realistically analyzing WDN behavior by overcoming existing limitations and simplified assumptions. Nonetheless, the transfer process of research efforts to practitioners is often hampered by difficulties in integrating new methodologies into existing software architectures, which might require complex changes of existing codes in order to incorporate new input data and analysis procedures. In addition, practitioners are often averse to move from tools/methodologies they are familiar with to newer ones, although they are proved to provide more consistent WDN analyses and effective decision support.

The WDNetXL, Giustolisi et al. (2011), is a system recently developed at Technical University of Bari which makes available the latest methodologies for WDN analyses, management and planning in Microsoft Office Excel (MS-Excel). The research transfer paradigm underlying WDNetXL system is based on the recent capabilities of high level computing languages (widely used among researchers) which permit to deploy new applications as functions in MS-Excel. This technological expedient, in turn allows to:

- easily implement and test new procedures;
- use any (even customizable) input data structures;
- make them readily available to final users (i.e. technicians, researchers or even university students).

In fact, MS-Excel is one of the most used data management tool worldwide. It is also compatible with several database formats, is fully integrated with a number of functionalities (i.e. data plotting, basic statistical analyses and so on) and permits to use the interoperability within the MS-Office package (e.g. text editing and/or multimedia presentations). Exploiting all these features of MS-Excel makes the WDNetXL system an ideal platform to facilitate the training of technicians in facing the complex problems of WDN analysis and management by using the most advanced research achievements in this field.

The latest version 3.0 of WDNetXL is structured into three main application areas concerning "Analysis", "Design" and "Management" of WDN. All sections share the same data structure, which is composed of tables in MS-Excel.

The "WDNetXL Analysis" entails advanced WDN steady-state hydraulic simulation (both snapshot and extended period) even accounting for topological modifications due to pipe failure events; analysis of the Isolation Valve System (IVS) and detection of existing District Metering Areas (DMAs) (as detailed in the following).

The "WDNetXL Design" section contains some functions dedicated to solve different design problems including: sizing of pipes and pumping systems; design of IVS; optimal allocation of pressure measurement devices; optimal design of segments/modules (i.e. DMAs). Two additional functions are also aimed at supporting decision on optimal sizing of pipes and tanks together with optimal control of pumps in terms of ON/OFF time scheduling or the level of tanks controlling pump activation.

The "WDNetXL Management" section comprises some functions for the advanced analyses, planning and management of WDN including the analysis of mechanical and hydraulic reliability, and optimal operation of pumps (i.e. by scheduling time or by setting the water levels in relevant controlling tanks). In addition, a function for the automatic calibration of the WDN model permits to assess roughness and leakage parameters based on available pressure and flow observations.

From WDN analysis perspective, the model used to solve the hydraulic simulation permits to accurately reproduce all elements including pressure and flow control valves, directional devices, pumps and variable level tanks. Moreover, differently from classical WDN simulation which was based on fixed demand at nodes (demand – driven analysis), all water demand components (Giustolisi and Walski, 2012) can be explicitly included by accounting for their dependence on pressure (i.e. pressure-driven analysis). This feature is of primary importance to realistically assess leakage water volumes and the energy consumption for pumping water.

4. Decision support paradigm in WDNetXL

Many functions reported in the "Design" and "Management" sections of the WDNetXL system are conceived to provide a decision support for solving different technical problems, which usually involve multiple objectives that are conflicting with each other. For example, in the pump scheduling problem, the energy cost for pumping usually increases during the off-peak water request hours (i.e. according to typical energy tariff); nonetheless, the increase of pressure regime due to pumping during off-peak demand hours results into larger water loss volumes (Giustolisi et al., 2013). Moreover, the technical solutions are often composed of a discrete number of alternatives for the decision variables (e.g. time intervals during which pumps are turned on/off), thus making most of the technical problems on WDN combinatorial.

In WDNetXL such problems are explicitly formulated as multi-objective optimization, where each objective reflect a technical criterion for searching optimal solutions. Accordingly, there is not one single "optimal" solution to the problem but, rather, a set of optimal "alternatives", each representing a trade-off between all the technical criteria. This set of solution is named "Pareto optimal set" and represents a practical tool for supporting engineers during the decision making process.

In fact, the solutions belonging to the Pareto set entail optimal compromises with respect to all technical decision criteria. The final selection among them can be driven by comparing optimal alternatives with each other or applying some other management criteria (e.g., budget allocation), not yet explicitly considered during the optimization.

The search for solutions of such discrete and combinatorial optimization problems, representing different WDN analyses and management issues, is performed in WDNetXL by using a multi-objective genetic algorithm named OPTIMOGA, Laucelli and Giustolisi (2011).

It is also worth noting that all WDNetXL functions permits to:

- decide a priori the candidate decision variables according to technically feasible alternatives defined by the user (e.g. pipe diameters, pump characteristics and possible tank size when a WDN upgrade has to be designed);
- account for existing elements (e.g. existing pipes which should not be re-sized), thus permitting the upgrade of the existing systems besides the design of new WDN.

The first point is useful to reduce the search space of alternatives and, thus, improve the efficiency and efficacy in finding the optimal Pareto set of technically feasible solutions.

The second point allows technicians to iteratively run the decision support functions by progressively fixing those elements which fulfills the expertise of technicians on the peculiar system. This last feature is of great relevance in order to gradually introduce the WDNetXL decision support paradigm into current management practices of Chinese water utilities where the decision making is mainly "experience based".

Although some of the objective functions optimized in WDNetXL are of general applicability, the ease of modification of the source code permits to easily incorporate and test other customized criteria/objectives, which may reflect peculiar management need of Chinese water utilities.

In the following of the paper, the WDNetXL decision support paradigm is exemplified by performing the optimal design of the DMAs in a portion of a Chinese pilot WDN, as provided by one of the project partners. This example is actually a part of the preliminary analyses to be performed in the first phase of the cooperation project.

5. DMA design in WDNetXL

The problem of optimal design of DMAs has been faced by a number of authors in the last decades (e.g. Swamee and Sharma, 1990; Walski et al., 2003; Diao et al., 2013). In the WDNetXL system the problem of DMAs design is formulated as a multi-objective optimization problem where decision variables are the locations where flow meters should be installed (i.e. along pipes) in order to observe inlet/outlet discharge at each district. In addition, it is assumed that pressure measurement gauges can be installed at nodes close to flow measurement devices; in fact, in real WDN such devices are usually installed into manholes that can be easily accessed by crews.

In more details, for a given set of flow meters, the network components (districts) can be identified by using network decomposition analysis which resorts to graph theoretic. In WDNetXL the block decomposition method is applied on the network topological matrix, which is also used to perform WDN hydraulic simulation, Giustolisi and Savic (2010).

The solution strings inside the GA (i.e. individuals) are coded as binary values that indicate the presence or absence of a flow measurement point at candidate locations (pipes). It is assumed that pipes connecting tank/reservoirs to the network, flow/pressure control valves and pumps are always equipped with flow meters. In addition, before running the DMA design function in WDNetXL, it is possible to decide whether all pipes are candidate for placing flow measurement gauges or, rather, only pipes close to non-serial nodes (i.e. joining more than two pipes) should be considered as candidate locations. Indeed, it can be argued that placing flow meters close to non-serial nodes can be useful to observe more than two districts with the same pressure meter; *vice versa*, installing flow meters along serial trunks (i.e. joining two pipes only) can be useful to further refine network monitoring inside existing DMAs.

Finally, it is assumed that flow meters can be installed where isolation valves (gates) already exist along some pipes, since they can be easily operated to isolate adjacent DMAs. This is actually a crucial aspect to make this decision support procedure acceptable in those utilities where management decision are mainly "experience based" and technicians are prone to drive the search by including their own expertise (in terms of "existing" valve locations). Moreover, technicians are allowed to iteratively run the DMA design function by progressively fixing the flow measurement points (among those suggested by the WDNetXL function) according to their expertise.

The search for optimal solutions of the DMAs design problem is performed by simultaneously minimizing two objective functions.

The first objective is the total number of flow and pressure observations which emulates the cost for installing pressure and flow measurement devices. Thus, minimizing it is supposed to drive the search towards cheapest solutions.

The second objective entails technical rationales and is formulated to drive the search towards:

- homogeneous DMAs in terms of both length of pipes in each DMAs and number of elements (i.e. pipes and nodes); it is noteworthy that pipe length can be related also the demand distributed into each district by assuming the same demand distributed per unit pipe length;
- the maximum number of DMAs identifiable with the minimum number of observations;
- the installation of flow meters along those pipes with the maximum expected flow rate; in fact pipes with the largest flow rate are likely to represent crucial mains in the network, carrying water through network sub-portions instead of just distributing water to connected customers.

It is evident that, in order to compute such objective functions, each candidate DMA configuration (i.e. individual of the GA) is evaluated in terms of both the topological elements and the hydraulic simulation to predict the flow through potential flow observation devices.

Due to its flexibility, the DMAs design function can be easily modified to accommodate different criteria (i.e. as objective function) that may reflect system peculiarities, like the singular urban contexts in the Chinese systems.

6. Application on pilot study area

The pilot system used herein comprises 253 pipes and 244 nodes, whose layout is reported in Fig. 1. The system is fed by a variable speed pump which assures a constant pressure at node designated with Ho in Fig. 1; for this reason the model provided includes a reservoir whose total head is 40m. The network is also equipped with 24 valves which permits to isolate 16 pipe segments, as reported in Fig. 2; there is just one valve (signed with a red circle in Fig. 2) which is not useful to separate two segments. Nonetheless, all these valves are pressure control valves where pressure and flow meters are installed and can be used to monitor the DMAs.

The DMA design function in WDNetXL has been used here to find the optimal location of flow and pressure control devices that can be used to identify effective DMAs, by contemporarily minimizing both objectives reported above. This means that a solution with a larger number of observations will be included in the final Pareto set if it will result into a further minimization of the second objective (i.e. technical rationales).

Fig. 3 reports the Pareto front of optimal solutions, as produced by WDNetXL, where optimal DMA layouts are reported in the two-objectives space (i.e. total number of flow/pressure observation vs. the second objective function). 35 DMA configurations are found which consists of an increasing number of observations (i.e. flow or pressure meters to be installed) at non serial nodes, starting from those already existing in the WDN.

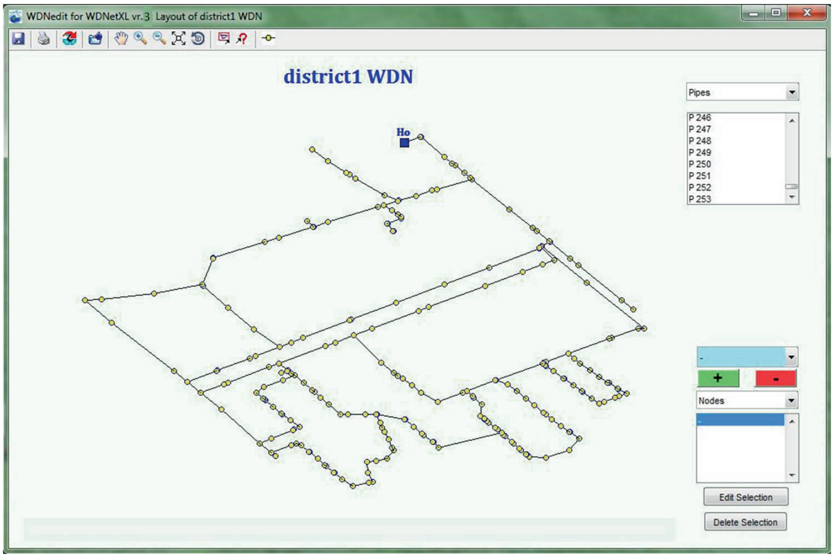

Fig. 1. Network layout

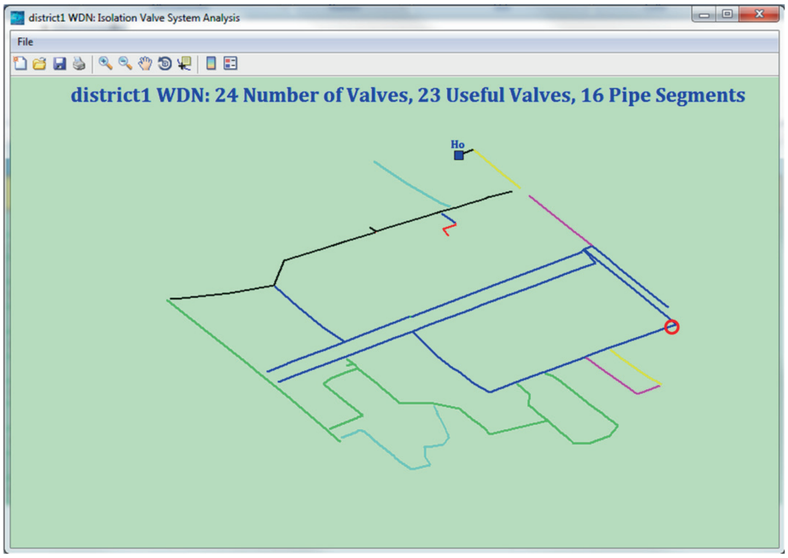

Fig. 2. Existing Isolation Valve System

The solution indicated with “A” in Fig. 3 just includes one more flow measurement, located along the pipe linking the reservoir to the network (circled in Fig. 4), while the reservoir itself is considered to provide a pressure measurement. The total number of flow and pressure observations which permits to identify separate DMAs is 48 (i.e. 24 flow observations + 24 pressure observations). In fact, for this solution, the pressure and flow meters located at “non-useful” valve (red circle in Fig. 2) still provide measurement only inside the same DMA.

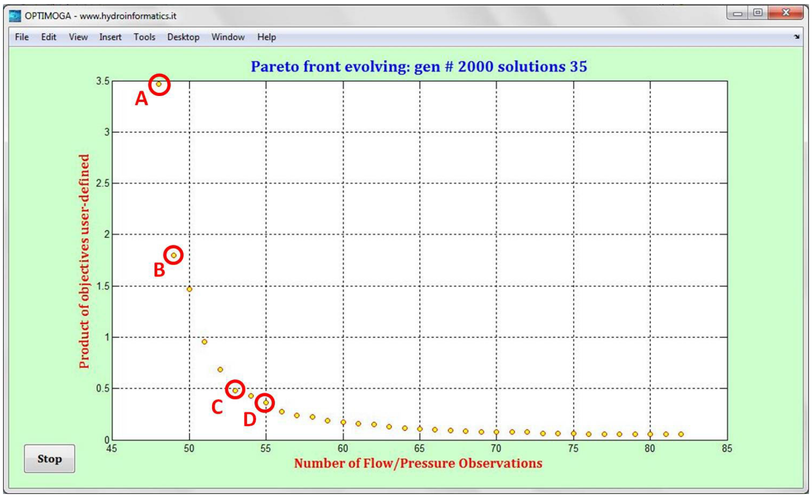

Fig. 3. Pareto front of optimal DMAs layout.

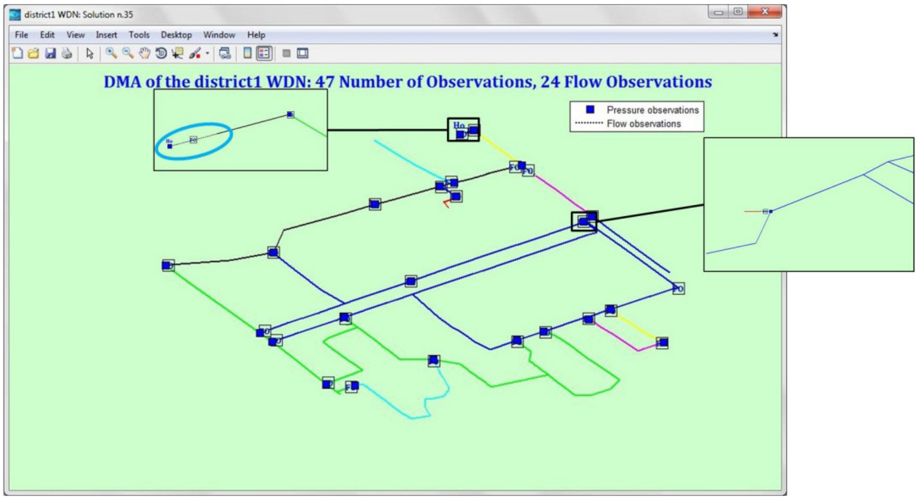

Fig. 4. DMAs layout of solution “A” in the Fig. 3 (16 DMAs).

Fig. 5 reports the DMA layout of solution “B” on the Pareto front, which is obtained by adding one flow meter and one pressure observation al location signed with a circle (the original network layout is reported in the box on the right side of Fig. 4); this permits to create an additional DMA (reported in red) and halves the second objective function value (i.e. increasing the matching of technical criteria). It is worth noting that also in this solution the “non-useful valve” belong to the same DMA.

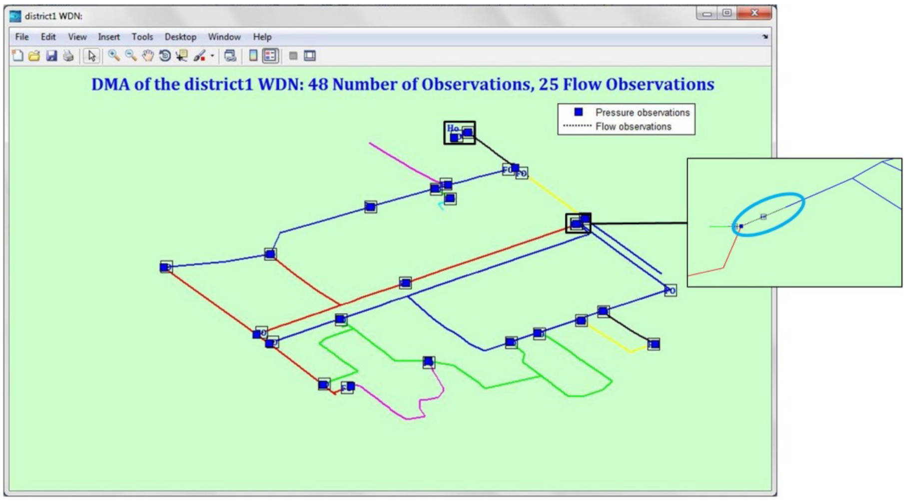

Fig. 5. DMAs layout of solution “B” in the Fig. 3 (17 DMAs).

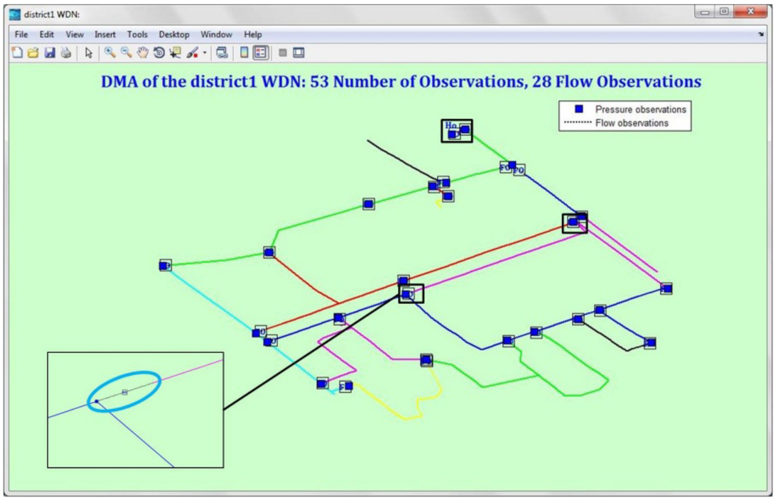

Fig. 6. DMAs layout of solution “C” in the Fig. 3 (19 DMAs).

A different configuration is reported in Fig. 6 where the addition of just one flow and pressure observation point permits to create an additional DMA for which the previous “non-useful” valve is now useful to observe pressure and flow. From a decision support perspective, Fig. 3 clearly shows that such DMAs configurations is quite better than the previous ones in terms of technical criteria, as demonstrated by the value of the second objective function, which is comparable with that achievable by further increasing the number of meters to be installed.

For the sake of completeness, Fig. 7 reports the DMA layout of solution “D”, which adds two more observation points, circled in the magnifying boxes. As for the other observation points, the new flow meters are put on pipes carrying high water flow and permits to further increase the number of DMAs up to 21.

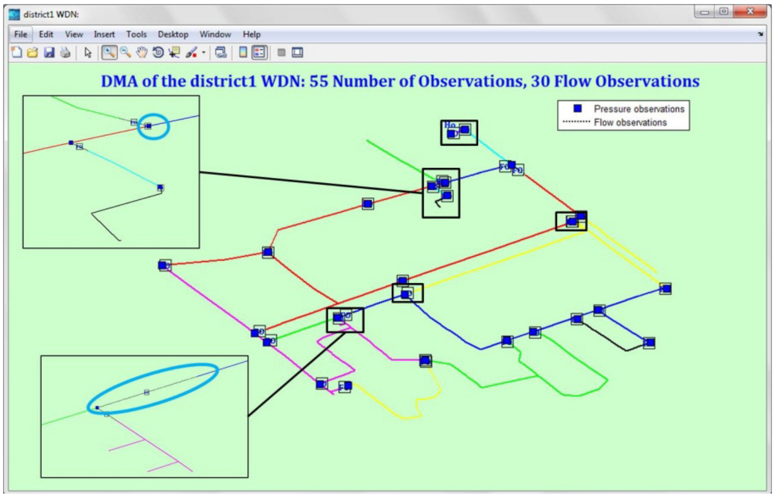

Fig. 7. DMAs layout of solution "D" in the Fig. 3 (21 DMAs).

7. Conclusions

Supplying water to people in the complex and rapidly changing Chinese environment requires sophisticated and flexible decision support tools to be used by water distribution experts. This paper summarizes the decision support paradigm of the WDNetXL system which will be used for technology transfer in the joint Italian-Chinese cooperation project.

The preliminary application of the WDNetXL system to support the design of DMAs on a Chinese pilot network demonstrates that formulating the technical problems in terms of multi-objective optimization within the WDNetXL permits to explore the global space of candidate alternatives. Such approach leave the selection of the most suitable alternative(s) to technicians also based on their own expertise.

The application of the same decision support paradigm for the sustainable management of WDN to be developed in this research project is aimed at reducing energy consumption and greenhouse gas emissions associated to pumping water through the pipelines and water losses. This, in turn, pursues the preservation of energy and water resources for future generations.

References

Diao, K., Zhou, Y. Rauch, W., 2013. Automated creation of District Metered Area boundaries in Water Distribution Systems. Journal of Water Resources Planning and Management 139(2), 184-190

Farley, M., Trow, S., 2003. Losses in water distribution networks, IWA publishing, London, UK.

Giustolisi, O., Savic, D.A., 2010. Identification of segments and optimal isolation valve system design in water distribution networks. Urban Water Journal, Taylor & Francis, UK, 7, 1 – 15.

Giustolisi, O., Savic, D.A., Berardi, L., Laucelli, D., 2011. An Excel-based solution to bring water distribution network analysis closer to users. In: D.A. Savic, Z. Kapelan, D. Butler (Eds) - Proceedings of Computer and Control in Water Industry (CCWI), September 5-7, Exeter, UK, Vol. 3, 805-810.

Giustolisi, O., Walski, T.M., 2012. Demand Components in Water Distribution Network Analysis. Journal of Water Resources Planning and Management 138, 356-367

Giustolisi O., Laucelli D., Berardi, L., 2013. Operational optimization: Water Losses vs. Energy Costs. Journal of Hydraulic Engineering 139, 410-423.

Laucelli, D., Giustolisi, O., 2011. Scour depth modelling by a multi-objective evolutionary paradigm. Environmental Modelling & Software 26, 498-509.

Swamee, P., Sharma, A., 1990. Decomposition of Large Water Distribution Systems. Journal of Environmental Engineering 116(2), 269-283.

Walski, T. M., Chase, D. V., Savic, D. A., Grayman, W., Beckwith, S., Koelle, E., 2003. Introduction to water distribution modeling; using models for water distribution system design. Advanced Water Distribution Modeling and Management, Vol. 4, 1st Ed., Haestad Press, Waterbury, CT.